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[*Continued on page (III) of Cover.*

THE DESIGN AND OPERATION OF HAMS HALL POWER STATION

By F. W. LAWTON, Member.*

(*Paper first received 20th October*, 1938, *and in revised form 5th January*, 1939; *read before* THE INSTITUTION *9th March, before the* SOUTH MIDLAND CENTRE *6th March, before the* NORTH-EASTERN CENTRE *13th March, and before the* TEES-SIDE SUB-CENTRE *5th April*, 1939.)

SUMMARY

To study a power station it is first necessary to isolate it from externals; but to understand it, to learn something of value from it, these external influences should be considered as they determine design and override operation.

The paper attempts not only to describe but also to explain both the design and the operation of Hams Hall power station, and to elicit from available data such guiding principles as may be deemed cogent to power-station engineering in general.

So many are the subjects that demand attention, that for the most part it has been necessary to limit consideration of details and for the sake of unity to treat the whole power station as one composite machine, and to select for detailed examination only those features that more particularly control the economic aspect of power production.

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INTRODUCTION

The time required to design, construct, and put to work, even the first section of a large power station is about 3 years, whilst to complete the entire plant may well take another 9 years, as was the case with Hams Hall.

The original design and layout can therefore be 12 years old before the last machine is generating, and the designer knows full well how difficult it is to introduce subsequent yet important innovations during construction over so long a period; the heat-cycle and steam conditions initially chosen are alone sufficient to dominate the fundamental design and to set a limit upon subsequent change.

Hams Hall was never intended to become a high-thermal-efficiency station, but was designed primarily to utilize economically cheap local low-grade fine slack coals under prescribed operating and local conditions, and only in so far as the station approaches this objective can the design be justified.

The object of this paper is to give to the power station engineer a comprehensive view of the design and operation of Hams Hall station over a number of years.

It has therefore been necessary to include in the paper some descriptive matter and technical data relative to the plant installed, but this has been kept to a minimum consistent with clearness, as already a more detailed description of the design has appeared in the technical Press.

An attempt has been made to correlate all data to general statements where this has been deemed practicable, and in the concluding paragraphs an outline of the principal lessons to be learnt is included.

Every power station is essentially different from others in some respects, and relatively few general principles are common to all; even these principles undergo time change, and so every power station designer must build anew and, whilst he may benefit by the experience of others, he can ill afford to copy what has gone before or his design will be out of date before it is well begun.

There is no royal road to the economic generation of electricity in the future. All the well-worn paths lie far behind us—a body of experience that can be used but

* City of Birmingham Electric Supply Department.

sparingly and with discretion amid changing economic conditions and ideology of modern minds.

GENERAL LAYOUT

The site, situated in the valley of the River Tame some 9 miles north-east of the city centre, is nearly a thousand acres in extent and was formerly sparsely wooded, agricultural, and park land known as Hams Hall Estate, at one time the country seat of Lord Norton, from which estate the station derives its name.

The site was chosen for its proximity to the sewage effluent outfall from the Birmingham, Tame, and Rea District Drainage Board's Sewage Works, whence sewage effluent flows daily into the River Tame and is used as make-up circulating water for the cooling-tower system.

The site is also close to the Warwickshire and South Staffordshire coalfields, and owing to its contour not less than 300 acres of low-lying flood land bordering on the River Tame is available for ash disposal for many years to come.

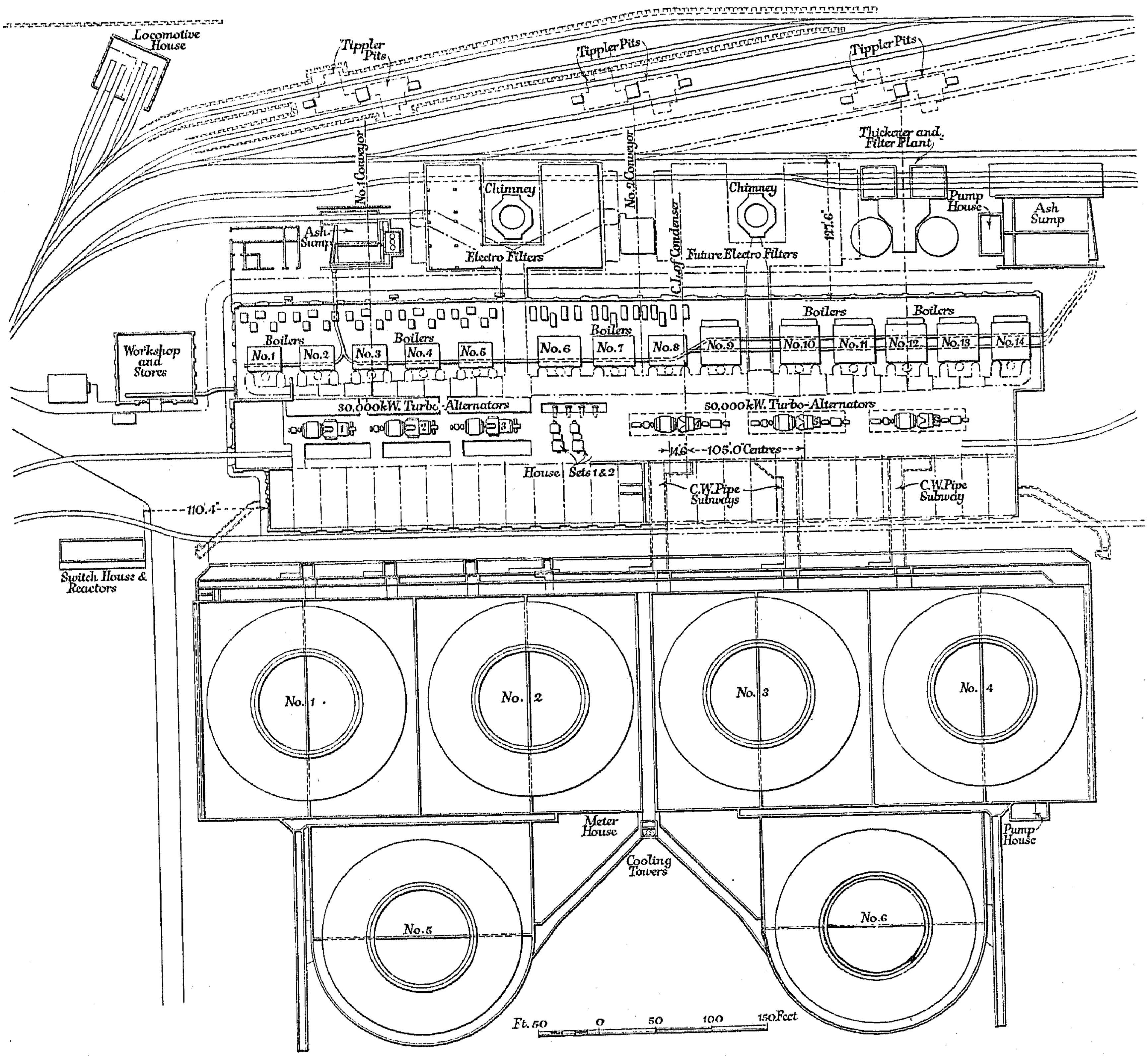

Fig. 1

Planned for simplicity, the general arrangement comprises a single row of 14 boilers housed adjacent and parallel to a single end-on row of 6 main turbo-alternators, with a symmetrical group of 6 cooling towers, as shown in Fig. 1.

The coal-handling plant is of the simplest—wagon tipplers, and bucket and belt conveyors—and the ash-

handling plant is a sluice and settling sump for heavy ash and a rotary filter for fine ash.

The first 8 boilers are fired with pulverized fuel, and the exit flue gases pass through cyclone grit arresters and thence through electrostatic flue-gas cleaning chambers to a brick chimney stack 350 ft. high.

The remaining 6 boilers are stoker-fired units fitted only with cyclone grit arresters, and from these the exit flue gases pass direct to a second brick chimney stack of similar height.

The first 3 turbo-alternators each have an output capacity of 30 000 kW, and the second 3 an output capacity of 50 000 kW. All operate at 1 500 r.p.m. and generate 11 000 volts. Controlling switchgear of the cellular type is arranged in a switch-house adjacent and parallel to the turbine room.

The station was designed in 1926, before official attention had been directed to fire-protection features, before the ugly spectre of war cast its dark shadow across the threshold of power-station design, and before protection against hostile air-raids was even remotely contemplated.

PART 1.—DESIGN

Buildings and Civil Engineering Works

The site has a reasonably uniform sub-soil of marl, loaded to a maximum of $3\frac{1}{2}$ tons per sq. ft.

All foundations are of ferro-concrete, 5 100 cubic yards for the superstructure, 7 200 cubic yards for the turbo-alternators, and 1 200 cubic yards for the boilers.

The superstructure of structural steel weighs 7 200 tons and is designed in accordance with the L.C.C. Regulations, the tallest stanchion being 80 ft. 6 in. high and the heaviest loaded stanchion supporting 410 tons.

The largest built-up girders are those over the boilers, with a span of 47 ft. and a depth of 6 ft. 6 in.

External walls are of brickwork, generally 9 in. thick, having a total surface of 156 700 sq. ft.; the windows, having an area of 24 200 sq. ft., represent 15·4 % of the total external surface.

Hollow concrete blocks $5\frac{1}{4}$ in. deep are used for all roofs, which together have a total area of 163 400 sq. ft. and are glazed to the extent of 54 000 sq. ft., or 33 % of the total surface area.

Generally all floors are of reinforced concrete 6 in. thick, supported on steel beams and finished with granolithic $1\frac{1}{2}$ in. thick. The floors are all designed for 2–$3\frac{1}{2}$ cwt. per sq. ft., the turbine-room basement being designed for 5 cwt. and the boiler-house basement for 4 cwt. per sq. ft.

All internal galleries are of steel grid construction, stairways being not less than 2 ft. 6 in. wide and inclined not more than 45 degrees to the horizontal.

For comparison with other stations the volumetric capacity of the several buildings is given in Table 1.

Two 350-ft. brick chimneys, constructed of Accrington "Nori" acid-resisting bricks set in hydrolysed lime mortar, have been built, each to handle 880 000 cu. ft. of flue gases per minute at 315° F.

The internal brick course, $4\frac{1}{2}$ in. deep, has been set in "Cement Prodor" (acid-resisting cement). At the base each chimney wall is 4 ft. 6 in. thick, having a maximum toe stress of 15 tons per sq. ft. with a wind pressure of 20 lb. per sq. ft. on the projected chimney area.

Each chimney weighs 5 200 tons and is supported on concrete foundations 7 ft. 6 in. thick having an area of 3 090 sq. ft., comprising 858 cubic yards of concrete and 48 tons of steel-bar reinforcements; the maximum ground pressure is 2·5 tons per sq. ft.

Externally the superstructure has plain classic features with few architectural adornments, and, save for moulded stone sills and cornices, is a red-brick structure entirely functional in contour and not shaped to achieve any ambitious architectural style.

The total area of roads and pavings is 12 900 sq. yd. The roads are constructed of 9-in. pitching on ashes 6 in.

Table 1

VOLUMETRIC CAPACITY OF BUILDINGS

Description	Volume	Area
	cu. ft.	sq. ft.
Boiler house	4 895 000	59 500
Electro-filter plant house ..	552 000	9 200
Turbine room	3 715 100	56 250
Switch-house	1 952 000	35 000
Total for main buildings ..	11 114 100	159 950
Per kilowatt of generating capacity	44·5	0·641
Workshops	130 000	4 340
Miscellaneous buildings ..	185 210	11 720
Total for all buildings ..	11 429 310	176 010
Per kilowatt of generating capacity (249 450 kW) ..	45·8	0·705

thick, surfaced with 3 in. tarred granite chippings and finished with 1 in. macadam.

Footpaths are of $2\frac{1}{2}$-in. pressed granolithic slabs laid on ashes 6 in. thick.

The drainage system is self-contained, the main sewer being 12-in. to 15-in. bore, fall 1 in 400; storm-water drains 6 in. to 18 in. bore, fall 1 in 200.

A separate sewage-disposal works for sewage and sludge, designed to treat a flow of 50 000 gallons per hour, has been constructed.

There are no unique civil engineering works which would repay detailed description, nor have abnormal difficulties been encountered in constructing the foundations or superstructure.

All coal supplied to the station is rail-borne in 10–12-ton railway trucks; the sidings accommodation for full trucks is 297 (or 3 000 tons) and for empty trucks is 342 (or 3 500 tons), the present average daily fuel consumption being about 2 000 tons.

The total single-track length is $6\frac{1}{2}$ miles, with a maximum gradient of 1 in 160 and a minimum radius of 150 ft., the normal radius of curves being 200 ft.

Loaded trucks are fed to the 6 tippler platforms by gravity sidings, gradient 1 in 260, which accommodate, in

all, 84 full trucks before the tipplers and 74 empty trucks after the tipplers.

All rail tracks are 80-lb./yd. standard steel rails, laid on 10 in. × 5 in. sleepers laid about 3-ft. centres.

Coal

The station was designed to utilize principally local bituminous low-grade fuels, variable in quality and obtainable from over 70 different local collieries from 7 to 70 miles distant from the power station. The action of the Co-ordinating Coal Committees appears to be resulting in a wholesale levelling-up of prices irrespective of quality or haulage distance, thus tending to offset the economic advantage of obtaining fuels from nearby pits readily accessible and low in rail charges.

The basic fuel has the following dry characteristics:—

	Pulverized-fuel boilers	Stoker-fired boilers
Calorific value—B.Th.U./lb.	10 000	12 100
Volatile matter ..	28 %	32·6 %
Ash	25 %	14 %
Hydrogen	3·75 %	4·6 %
Through $\frac{1}{8}$-in. mesh	20 %–90 %	Not exceeding 50 %
Coking index (Campredon)	—	Not less than $4\frac{1}{2}$ %

The average characteristics for fuel as delivered are:—

Description	1935	1936	1937
Fuel burnt per annum, tons	294 654	439 061	640 793
Average calorific value as received—B.Th.U./lb.	10 006	9 934	10 087
Average ash content, as received	13·5 %	13·75 %	12·90 %
Average moisture content, received ..	12·7 %	13·2 %	12·95 %
Average price per ton, delivered	9s. $6\frac{3}{4}$d.	11s. $11\frac{1}{4}$d.	14s. $4\frac{3}{4}$d.
Amount of coal stocks, tons	16 079	22 832	33 443

Fifty-eight different fuels under contract over a period of 3 years show on test considerable variation in net calorific value, as follows:—

Variation in net calorific value—B.Th.U./lb.	Number of fuels	Tons burnt per annum (approx.)
Below 1 000	3	15 000
Between 1 000 and 2 000	27	220 000
Between 2 000 and 3 000	22	375 000
Above 3 000	6	30 000
Total =	58	640 000

Minimum net calorific value = 5 960 B.Th.U./lb.
Maximum net calorific value = 11 360 B.Th.U./lb.

The average coking indices of the fuels actually received are as follows:—

46 %	Less than 2
45 %	Between 2 and 8
9 %	Between 9 and 12

Fuel suitable for stocking is of higher grade than the average, and when stored on the ground to a depth of 12 ft. 0 in. is generally as follows:—

	Percentage fine through $\frac{1}{8}$-in. mesh
Nutty slacks	Up to 40 %
Washed slacks.. ..	Up to 50 %
D.S. nuts	Up to 4 %

Fuels are purchased on an order-of-merit basis, calorific value, boiler duty tests, coal- and ash-handling costs, all being taken into account to determine the highest effective heating value per penny of cost, including all charges.

This system worked well before the coal-selling schemes came into operation, and whilst this method of purchase has almost lost its usefulness at present, it serves to show the glaring discrepancies and inconsistencies in the coal price values now offered and proves that these values are arbitrary, are not based on real physical values, and are therefore adding unnecessarily to the cost of electricity production.

Coal-Handling Plant

All coal being rail-borne, the coal-handling plant is of the simplest design, consisting of wagon tipplers, and belt and bucket elevators with shuttle belts over the coal bunkers.

In all, three separate sets of coal-handling equipment are installed, each of uniform design and construction and each capable of handling 200 tons of coal per hour to bunkers, or 100 tons per hour to coal store.

Each set consists of two side-discharge wagon tipplers designed for wagons up to 20 tons capacity, equipped with automatic weighing machines fitted with a card-printing device.

From the wagons coal is discharged into a blue-brick-lined steel receiving hopper; it is then fed to a bucket conveyor and elevated to another hopper which feeds coal either to the inclined belt conveyor supplying the coal bunkers, or, alternatively, to a horizontal belt conveyor for stocking fuel on the coal store.

Coal is distributed to the several bunkers by shuttle-belt conveyors, and to stock by a travelling-belt distributor. This stocked coal is reclaimed by three 10-ft. rail-gauge steam jib cranes and dropped into travelling receiving hoppers serving the horizontal store belt conveyors, which are reversible in direction of travel.

Technical particulars of the coal-handling plant are given in Table 9 (see Appendix).

Boiler Plant

The steam-raising plant comprises 14 boiler units installed in 3 sections; the first 5 boilers are the straight-tube type having a normal evaporation of 180 000 lb. of steam per hour, and the second section comprises 3 bent-tube boilers of 250 000 lb. per hour capacity. All 8 units are fired with pulverized fuel on the unit system and are fitted with superheaters and plate-type air heaters, but have no economizers.

The third and last section comprises 6 chain-stoker-fired boiler units, each having a normal evaporative

capacity of 250 000 lb. per hour, fitted with superheaters, air heaters, and economizers.

The first section of the station was designed for a load factor of 30 % with coal at 10s. per ton, and, as pulverized-fuel-fired boiler units were chosen, economizers could not be economically justified owing to the high preheated-air temperature thus possible. However, such a high temperature is not practicable with chain-grate stokers, and thus economizers were justified for the stoker-fired boilers.

To prevent the passes of the plate-type air heaters from becoming choked with dust-moisture, hot air re-circulation is resorted to.

All combustion chambers are water-cooled by bare fin tubes on side and back walls, and by plain tubes on the front wall, while on all pulverized-fuel-fired boilers there are water-screen tubes arranged above the ash hopper.

Steam soot-blowers are fitted on all boilers.

All operation is carried out on the firing-floor level, which is continuous throughout the entire length of the boiler house, and on this level all motor starters and control panels are arranged.

Boiler galleries and stairways are constructed of steel-grid panels supported on steel framework independent of the building structure.

The main technical features of the boiler units are given in Table 10 (see Appendix).

Dust-, Grit-, and Ash-Handling Plants

The first section of the station was equipped with two shunt-pressure cyclone grit-arresters in parallel and one short steel chimney for each boiler unit.

The dust-collecting efficiency of these grit-arresters on the pulverized-fuel-fired boilers was about 75 %, which meant that about 1·25 grains of dust per cubic foot of flue gas was being emitted to atmosphere.

Under these operating conditions 8 %–10 % of the total ash in the coal was deposited in the heavy ash hopper below the boiler and was conveyed by water sluice, together with the fine ash from the cyclones, to an ash sump, from which the settled ash was removed by a telpher grab to ash trucks for disposal on the low-lying area of the site.

Considerable difficulties were experienced in settling-out the fine ash in the ash sump, and on microscopic inspection this fine ash was found to be largely composed of hollow spheres of silica which formed "floaters," often remaining on the water surface to a depth of 2 ft.

The fine ash which settled out also caused the bulk of the ash in the sump to set hard in about 12 hours, thus rendering it almost impossible to remove the ash from the sump by means of a telpher grab.

The Committee set up by the Electricity Commissioners to report on chimney emissions issued a report in 1932 recommending, amongst other things, electrostatic flue-gas cleaning plants with tall chimneys and demanding a standard of cleanliness of 0·4 grain per cubic foot of exit chimney gases discharged to atmosphere.

The electrostatic method depends for its operation on the ionization of gases by corona formed between electrodes maintained at a p.d. of 50 000–60 000 volts. The electrodes from which discharge takes place are of negative polarity; the dust particles thus become negatively charged by bombardment of the electrons in the ionized gas and are repelled by the negative electrodes and deposited on the positive electrodes, which are at earth potential.

The accumulated dust from the earth electrodes is disturbed by automatic rapping gear and deposited in dry-ash bunkers.

Such a plant was installed at Hams Hall in January, 1936 (together with three additional pulverized-fuel-fired boilers), and has to deal with dust of the following sizes:—

Over 63 microns diameter	2·0 %–10·0 %
Between 50 and 63 microns diameter	2·0 %– 5·0 %
Between 40 and 50 microns diameter	3·0 %– 6·0 %
Between 30 and 40 microns diameter	3·0 %– 8·0 %
Between 20 and 30 microns diameter	4·0 %–14·0 %
Between 10 and 20 microns diameter	8·0 %–27·0 %
Less than 10 microns diameter ..	50·0 %–75·0 %

As the ash sump was already inadequate and an added quantity of yet finer dust had to be dealt with from the electrostatic plant, an alternative method of dealing with this fine ash was sought in the adoption of a vacuum-filter plant, the only method then available for separating the water from the ash for handling purposes.

The whole of the fine dust from the cyclone grit arresters and the electrostatic plant is water-sluiced through an inclined trough to two thickener sludge tanks, the thickened sludge then being elevated by diaphragm pumps and slurry pumps to a container wherein revolves a linen-lined drum filter on which the filtered ash forms a cake containing about 20 % moisture, the surplus water being drawn off by vacuum through the filter cloth.

The caked ash is removed by a scraper and is deposited into ash bunkers and loaded into trucks for disposal.

The settled water from the thickeners is returned to the circulating system and re-circulated. Purging of the circulating water is necessary to prevent incrustation of insoluble salts in the pipe-lines.

The heavy ash from the 6 stoker-fired boilers is sluiced to a second ash sump and is easily removed by a telpher grab to ash trucks.

The ash is conveyed to the disposal ground by standard and narrow-gauge trucks and is distributed on the site by petrol-driven dumpers and diggers.

One of the most difficult problems connected with the subsequent addition of electro-filter plant was the design of the overhead flue-gas ducts, 19 ft. in diameter, supported on the existing boiler-house roof, to convey the flue gases from the existing short chimneys to the electro-filter plant. Constructional details of these ducts have already been published in the technical Press.*

Circulating-Water System

Make-up sewage effluent water is withdrawn from the outfall culvert through rotary screens and is pumped by 8 vertical-spindle motor-driven pumps (housed together) to the suction culvert of the cooling ponds, the total pumping capacity being 400 000 gallons per hour.

When the station is developing 240 000 kW the make-up loss due to evaporation in the cooling towers is about 190 000 gallons per hour, and to keep down the con-

* See *Engineering*, 1937, vol. 143, p. 511.

centration of the water about double this quantity has to be circulated as a maximum.

The circulating water for the condensers is withdrawn from the suction culvert of the cooling-tower ponds by separate pumps housed in the turbine room adjacent to each turbo-alternator.

As sewage effluent is highly powerful as a corrosive of mild steel, the circulating-water pipes are of cast iron, the steel pump shafts are sheathed with gun-metal, and the pump impellers are also of gun-metal.

The static head of water above the bottom row of condenser tubes is 31·6 ft. Adding this to the head corresponding to a vacuum of 28·3 in. Hg, a total pressure of 27·6 lb. per sq. in. exists between the water and steam space; hence the consequences of condenser-tube leakage are more serious than in the case of a low-head riverside station.

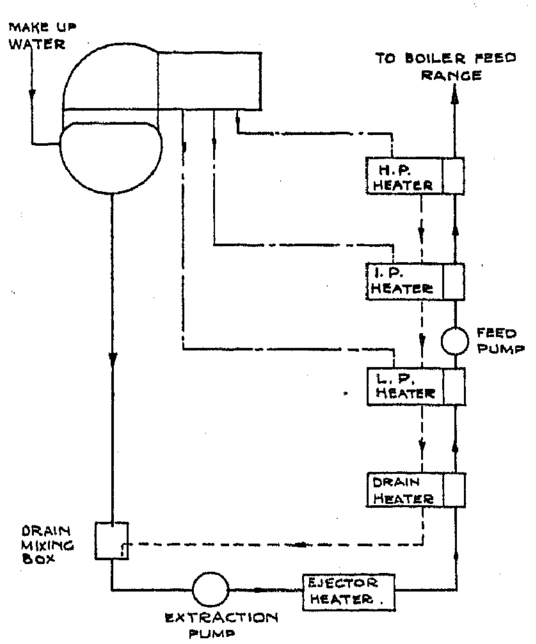

Fig. 2.—Diagrammatic arrangement of feed-water system—Nos. 1 and 2 sets.

Sewage effluent is also used for sluicing the ashes and dust from the boiler plant..

Feed-Water System

A ferro-concrete reservoir is constructed to contain 5 850 000 gallons of town water and is divided into two sections. If the water is hard it is first passed through a lime and soda plant capable of reducing the total hardness of the incoming water of 25 grains per gallon (expressed as $CaCO_3$) to not more than 5 grains per gallon at a rate of 12 000 gallons per hour. Now that soft water is available from the town supply, this plant is not normally required, and the water is passed direct to the storage reservoir and for make-up purposes is pumped through a Zeolite plant at the required rate. Analysis shows that the total hardness in the outgoing water does not exceed 1 grain per gallon (expressed as $CaCO_3$).

On reaching the station through duplicate pipes the water is stored in 6 reserve feed-water tanks, one for each turbo-alternator, the total reserve water quantity in the station being 92 000 gallons.

A diagrammatic arrangement of the feed-water circuit will be found in Figs. 2 and 3, from which it may be seen that the make-up feed water is admitted to the condensers and de-aerated, is mixed with the condensate, and passes with it through the several feed-water heaters to the boilers.

Cooling Towers

The whole of the sewage effluent circulating water is re-cooled in a battery of 6 ferro-concrete cooling towers each 210 ft. high, 168 ft. in diameter, hyperbolic in vertical section, and designed to cool 2 666 000 gallons of water per hour from 92° F. to 75° F. (wet-bulb temperature 52° F., relative humidity 80 %).

The maximum pressure on the ground does not exceed 2 tons per sq. ft.

Internally, the water distribution troughs are of red deal and the height of the inlet water is 35 ft. above ground-level.

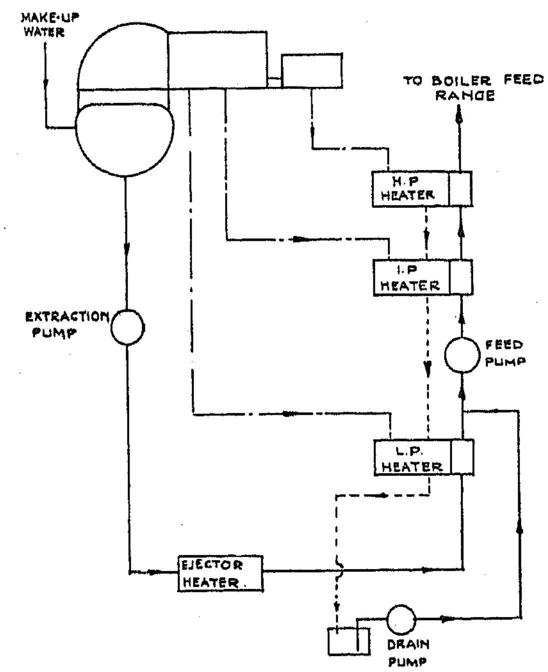

Fig. 3.—Diagrammatic arrangement of feed-water system—Nos. 4, 5, and 6 sets.

The towers are built above 6 ponds, each 9 ft. 6 in. deep, having a capacity of 1 736 000 gallons.

Each unit, comprising tower and pond, requires 9 700 cubic yards of concrete, 41 600 cubic feet of timber for irrigation troughs and laths, and 480 tons of steel reinforcement. The cost of each unit, including excavation, is approximately £50 000.

Fig. 4 shows a typical cross-section through one cooling tower and pond.

Fire-Fighting Equipment

To facilitate isolation of possible fires, the switch-house, which is in one main block, is divided vertically into three separate sections with walls and sliding steel fire-proof doors between.

All oil blown out from switch tanks under fault conditions is trapped and separately conveyed by pipes to the outside of the building. Raised concrete floor plinths are provided at the base of each switch tank to prevent the spread of oil.

All lagged steam pipes adjacent to turbine oil pipes are protected by steel cowls.

In and around the station 41 fire hydrants are installed, and on the coal store 21 are provided. All hydrants are

supplied with towns' water at 80 lb. per sq. in. pressure.

Portable " Fire-foam " extinguishers are located in the turbine room and switch-houses.

The main step-up transformers, arranged in open-sided bays with walls on three sides, are protected by an overhead " rose " to which foam may be pumped, via a pipe-line, from a foam machine situated in the engine room.

A diagram of the arrangement of the fire hydrants is shown in Fig. 5.

Heat Cycle

To understand the choice of heat-cycle and steam conditions it is necessary to review the position as it was in 1926, before the Central Electricity Board came into being, when only local conditions had to be studied.

At this time the Birmingham system load factor was less than 30 %, and coal having a gross calorific value of 10 000 B.Th.U. per lb. could be purchased for 10s. per ton delivered; moreover, a quantity of fine slacks at 8s. 6d. per ton was also available, and upon these conditions was the heat cycle chosen.

Another prime factor was that, cooling towers being essential, a heat cycle employing regenerative feed-heating to the maximum would reduce the cooling-tower capacity required for a given vacuum.

At this time also, pulverized fuel was little used in this country and total steam temperatures rarely exceeded 700° F.; further, economizers rather than air heaters were in general use in the boiler house, as chain-grate stokers did not take kindly to preheated air of high temperature.

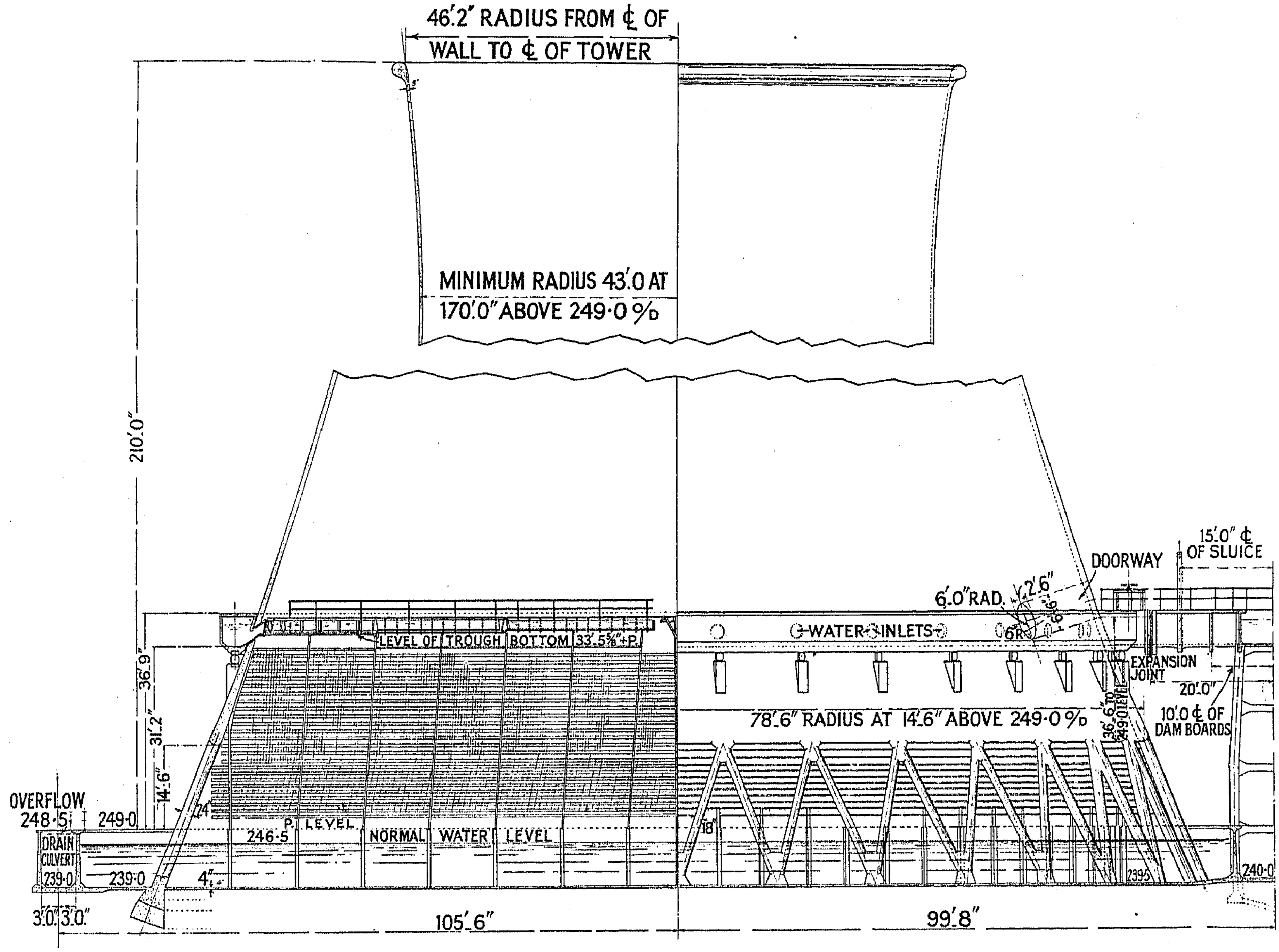

Fig. 4.—Cooling tower.

Much depends upon a proper choice of load factor; indeed, upon this and fuel price and quality the heat cycle, station design, and production costs, almost entirely depend. For example, with the load factor and coal prices prevailing in 1926, economizers were not economically justified with the regenerative cycle using pulverized fuel and preheated air. At 40 % load factor economizers could be justified, whilst at 60 % load factor the re-heat cycle is economically justified when using coal at 16s. per ton, notwithstanding the higher cost of plant involved.

The station load factor upon which the design depends should be the average load factor on the power station throughout its economic life. If the system load grows sufficiently to necessitate a second or third power station being built during the economic life of the first, then the

load factor on the first will be reduced, resulting in a lowering of the average load factor.

The total steam temperature at the turbine stop-valve having been fixed at 700–720° F., the economic steam pressure became 350 lb. per sq. in. by gauge, designed for a

Having regard to the moderate size of boilers installed, the economic difference between pulverized-fuel-fired boilers and stoker-fired units using the better fuels was negligible and, on the assumption that all slacks available could be dealt with on the pulverized-fuel-fired boilers,

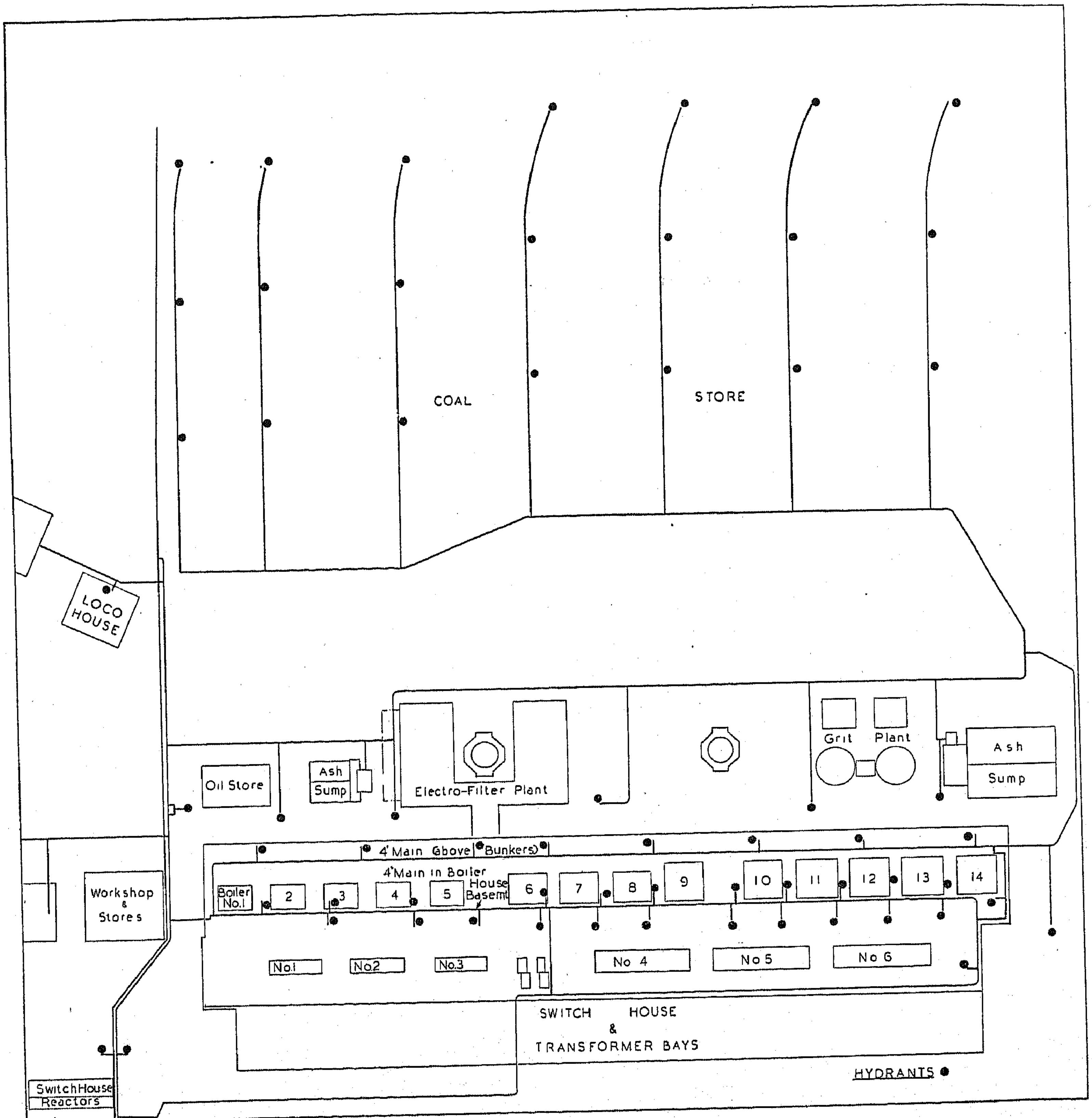

Fig. 5.—Diagram of fire-hydrant positions.

vacuum at the turbine exhaust flange of 28–28·3 in. Hg at economic rating.

As the existing pulverized-fuel boilers could consume practically all the fine fuels available from nearby collieries, the third section of the boiler house was equipped with stoker-fired boilers which could burn the more expensive fuels without much difficulty, thus eliminating the expense of electrostatic precipitation plant and separate fine-dust-handling plant.

turned slightly in favour of stoker firing when the savings on electro-precipitation and ash-handling costs were considered.

Considerable improvements have since been made in ash-handling plants and, if boilers of, say, 300 000 lb. per hour evaporative capacity are used, pulverized-fuel firing is to be preferred on economic grounds when using low-grade Midland fuels, particularly if cooling towers are essential.

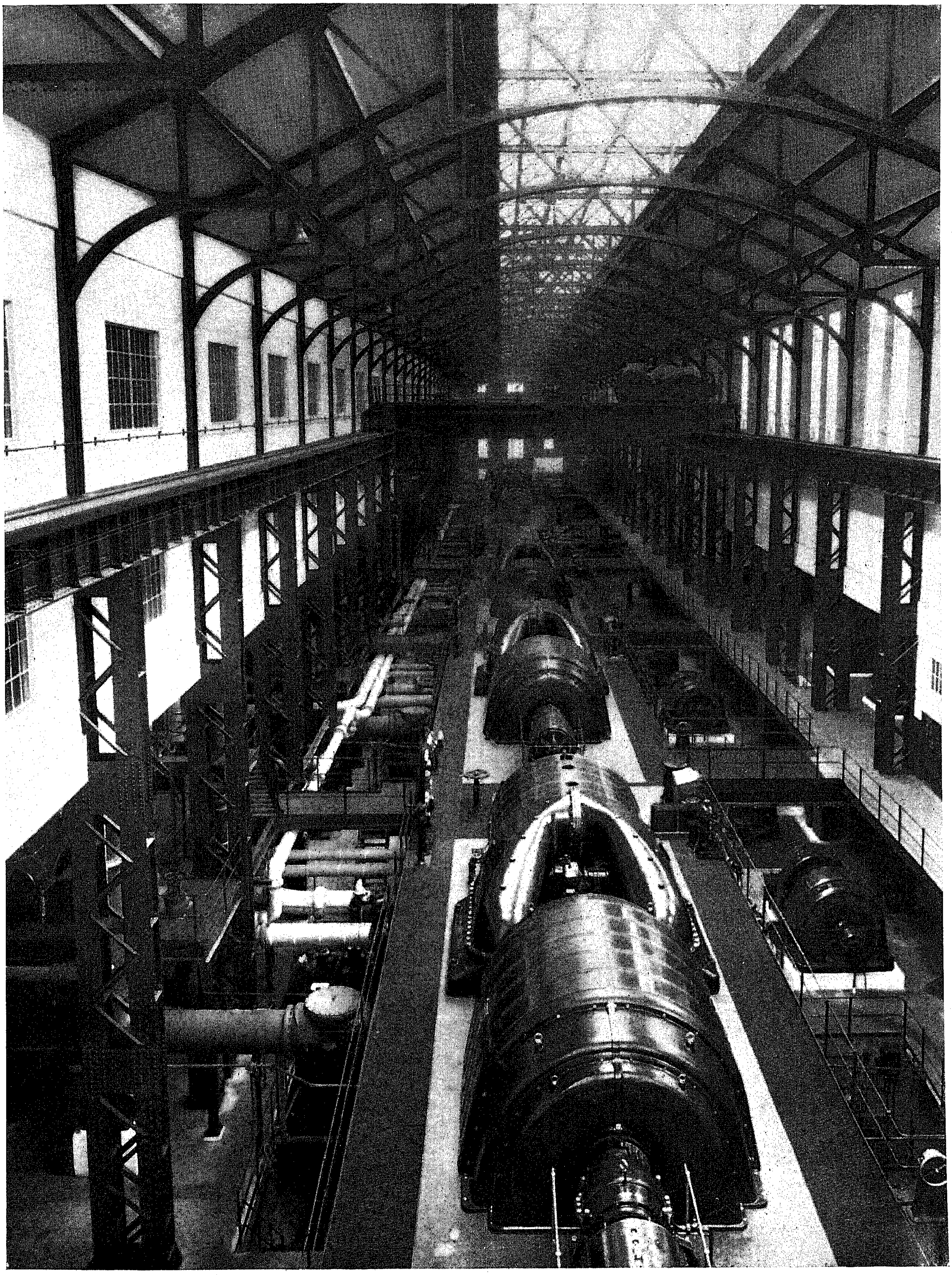

Fig. 6.—General view of turbine room.

Plate 2

Fig. 9.—Control room.

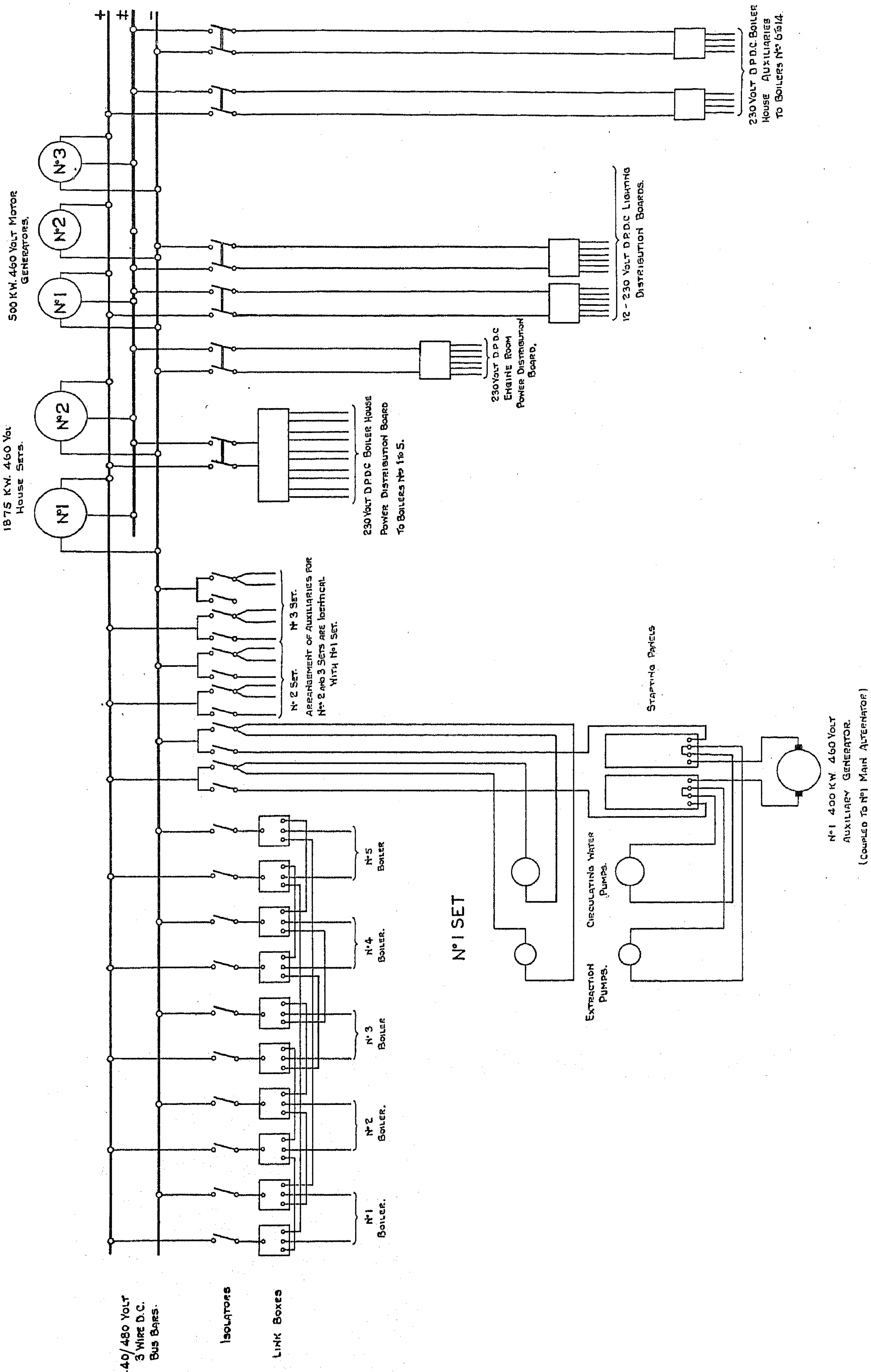

Fig. 7.—Works-supply 3-wire d.c. 460/230-volt system.

The particulars and technical performance of the first and second sections of the plant are given in Table 11 (see Appendix).

Turbines and Condensing Plant

(a) First Section.

The first half of the turbine room is equipped with three 30 000-kW (M.C.R.) single-casing impulse turbines each with a double row of velocity blades and 9 other rows of nickel steel, the remaining rows of blades being of stainless steel.

Steam sealing is by labyrinth packing on the rotor shaft, on which the wheels are pressed hydraulically. The rotor thrust is taken up by two Michell thrust bearings.

Two steam chests, each fitted with a stop and emergency valve and four throttle valves, are provided for each machine, designed for operating at 0·4, 0·6, 0·8, and full load respectively.

All relays are oil-pressure-operated, and main and standby oil pumps are fitted; the main oil tank arranged below the machine has a capacity of 1 300 gallons.

The condenser shells for each machine are of cast iron, tubed with $\frac{3}{4}$-in. (o.d.) Admiralty mixture tubes expanded in the tube plate at one end and packed at the other.

Two 60 %-full-duty motor-driven vertical-spindle centrifugal circulating pumps are installed per set. These operate against a total head of 61·5 ft., the condenser-tube friction drop being 6·6 ft. when the full-load water flow is 21 250 gallons per minute.

Two full-duty steam air ejectors and two full-duty motor-driven extraction pumps are provided for each set, and for the first two machines three boiler feed-pumps (two motor-driven and one steam-driven) are installed, capable of operating in parallel with each other, whilst the third machine has one steam-driven and one motor-driven feed pump.

(b) Second Section.

The second half of the station is equipped with three 50 000-kW (M.C.R.) tandem two-cylinder reaction-type turbines with 40 rows of moving blades in the high-pressure cylinder and 30 rows in the low-pressure cylinder, all of stainless iron, this being preferable to higher-carbon stainless steel as it is free from the danger of becoming brittle during manufacture.

Steam sealing is first by labyrinth and finally by carbon packing, the sealing steam being condensed, proper sealing being indicated by water-drip to open tundish.

The valve gear is oil-pressure operated and is connected to the turbine casing through flexible pipes.

The condenser shells for each machine are of cast iron tubed with $\frac{3}{4}$-in. (o.d.) Admiralty mixture tubes secured into the tube plates with Crane and Crane–Wilkie packing respectively.

Three half-full-duty motor-driven centrifugal vertical spindle circulating pumps are installed for each condensing plant, each pump operating against a total head of 57·78 ft., the condenser-tube friction drop being 8·86 ft. when the full-load water flow is 31 500 gallons per minute.

Three half-full-duty steam air ejectors and two full-duty motor-driven extraction pumps and two feed pumps (one motor-driven and one steam-driven) are provided for each condensing plant.

Steam Piping

For the first section the steam supply piping to each of the three 30 000-kW turbines did not exceed 16-in. bore, and sufficient flexibility was obtainable by means of plain expansion bends.

For the second section the steam supply piping to each of the three 50 000-kW turbines is in duplicate, with 12-in. bore mains, since a single pipe of 18 in. bore would have been too rigid.

Solid forged horizontal steam receivers 28 ft. long and 30 in. bore are installed, one for each 50 000-kW turbine, directly connected to two boilers and one turbine, with balance piping between adjacent steam receivers.

Push-button electrical control is arranged for operating the steam valves on the supply to each turbine and from each boiler.

All high-pressure steam drains are taken to tanks (vented to atmosphere) from which drain water is withdrawn by the extraction pump suction and thus mixed with the condensate from the main condensers.

The high-pressure steam piping is so designed that, under conditions of maximum stress, half the limit of proportionality of the metal at maximum temperature is not exceeded.

Where practicable all joints are welded, sleeve-welded joints being extensively used.

Main Alternators

All 6 main alternators are totally enclosed and generate 3-phase current at 11 000-volts between phases, each being ventilated by fans carried on the end of the rotor shafts.

The stator coils are insulated with mica and are contained in micanite tubes moulded on each conductor.

The rotor is of the drum type, a single solid forging bored and slotted. The rotor windings are insulated with mica, and the overhanging portions are bound with woven asbestos tape supported by asbestos blocks.

In order to reduce stray alternator losses, bakelite fabric is used to support the winding, arranged radially round the circumference.

The end clamps of the stator core are also magnetically insulated from the core by an aluminium press-ring and bronze plates.

On the outer end of each alternator shaft a direct-coupled generator and exciter is fitted.

A general view of the turbine room is given in Fig. 6 (see Plate 1, facing page 476), and technical particulars of the alternators are given in Table 13 (see Appendix).

Auxiliary Circuits

Much could be said with advantage about power station auxiliaries; their design and arrangement does not greatly depend on local conditions.

With pulverized-fuel firing the auxiliary power used on the works is greater than when stoker-fired boilers are installed; also inter-stage feed heating, high boiler pressures, and cooling towers, all add to the amount of auxiliary power required and so, whilst a small works consumption is desirable, it is not necessarily a criterion of success.

As ever, opinion is divided on the best way of arranging

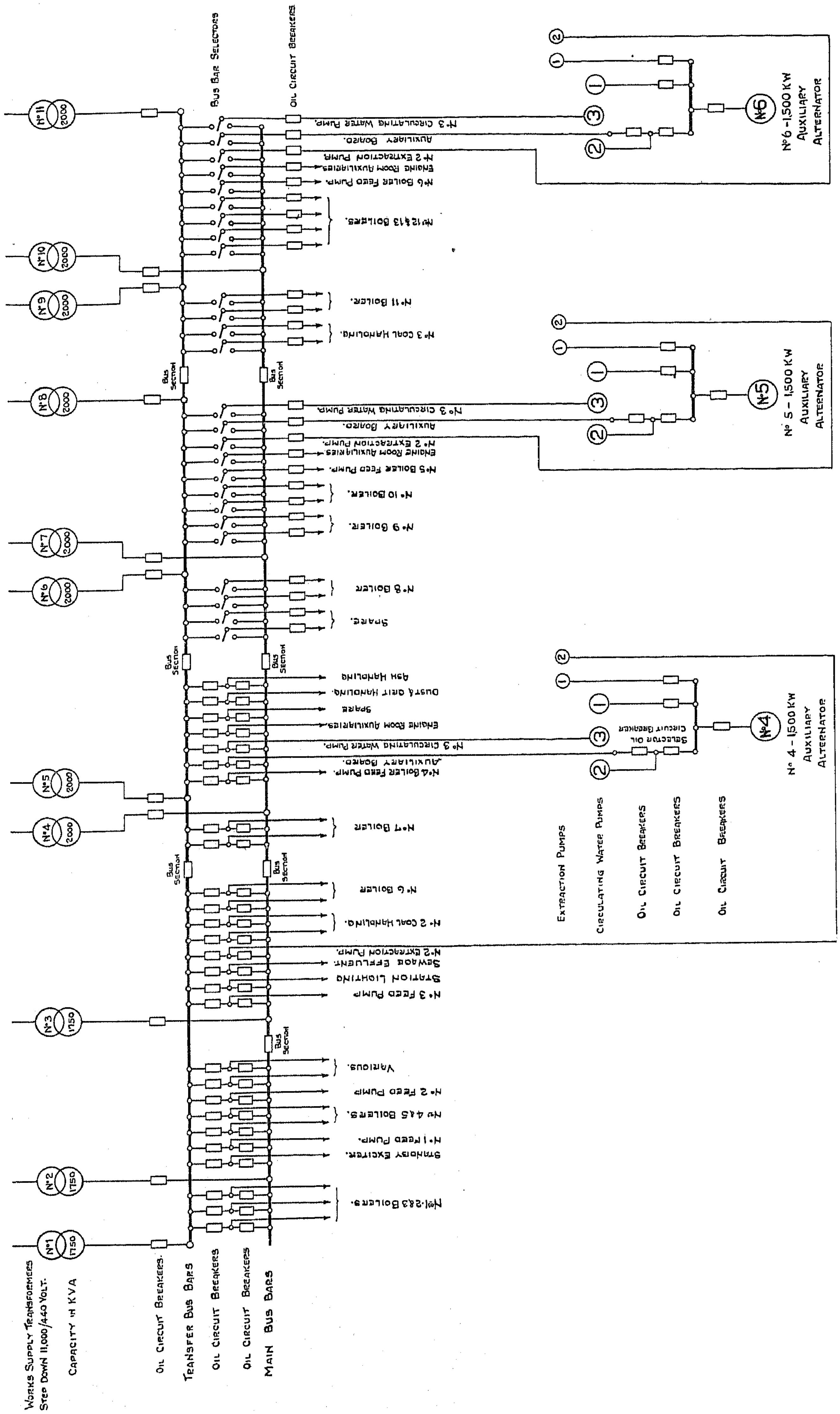

Fig. 8.—Works-supply a.c. 440-volt 3-phase 50-cycle system.

auxiliary circuits. Adherents to direct current can still be found, also opposition to direct-coupled auxiliary generators to the alternator shafts is prevalent.

There are even some who hold that steam-driven auxiliaries are better, but these hardly dare make their voices heard in face of opposing criticism based upon consequential thermal loss.

From an operating point of view steam auxiliaries have the advantage of being immune from external electrical circuit interruptions, yet their effect on the heat cycle is deplorable and they are costly to maintain, as are also steam-driven house service generators.

In the first section of Hams Hall two 1 875-kW (M.C.R.) turbo-driven d.c. generators were installed, operating in conjunction with 500-kW motor-generators driven from the main supply, together with a direct-coupled 400-kW d.c. generator on each main alternator shaft, all generating at a pressure of 440–480 volts for auxiliary supplies and totalling in all 6 450 kW of d.c. plant.

A diagrammatic arrangement of the d.c. auxiliary supplies is shown in Fig. 7.

In the second section d.c. auxiliaries were abandoned and a.c. generators, each of 1 500 kW, are direct-coupled to the last three 50 000-kW alternator shafts, supplementary supplies being obtained from 11 house transformers coupled to the main 11 000-volt supply.

All a.c. house supply is at a pressure of 400 volts and includes 21 250 kW of transformer plant.

A diagrammatic arrangement of the a.c. works supply circuits is shown in Fig. 8.

In the first section d.c. auxiliaries were chosen for speed control on boiler fans and the like and house turbo-generators, to ensure immunity from external electrical circuit interruptions.

Our experience has shown that these refinements are not economically justified and that a.c. auxiliary drive is satisfactory and cheaper to install and maintain.

Before deciding on the type of auxiliary drive for the new Hams Hall "B" Station, a careful analysis was made as to the relative merits of 400 volts (a.c.) as compared with 3 300 volts (a.c.), and on economic grounds they were found to be practically equal.

It was decided, however, to adopt 3 300-volt generators coupled to the main alternator shafts, with stand-by transformer supplies from the main circuit, all motors of 90 b.h.p. and over being supplied direct at this voltage.

This high voltage was chosen principally on the grounds of convenience in arranging auxiliary circuit cables, and the adoption of generators coupled direct to the main alternator shafts was decided on to give partial immunity from external circuit interruptions and also to give high economy.

In the new station house-service turbo-generators are not proposed, on the grounds of cost.

Control Room

The control panels for turbo-alternators, outgoing feeders, turbine-room telegraphs, and transformer indicator devices, together with temperature-indicating panels and grid meter panels, are situated in a central elevated control room commanding a view of the turbine room.

These panels are equipped with controls for operating electrically the various circuit-breakers, indicating lamps, synchroscopes, and synchronizing plugs.

The machine instrument and relay panels are fitted with indicating wattmeters, ammeters, voltmeters, and power-factor meters.

Switches for governor control circuits and for operating the generator neutral earth switches and exciter shunt field rheostats are installed to enable the station to be operated from the central control room.

All relays are wound to withstand 5 times full-load current, and the overload relays can be adjusted between 100 % and 200 % full-load current and a time-lag from 0·5 to 8 sec.

The alternators and main step-up transformers are equipped with neutral earthing resistances. The switches for these are so arranged that only one earthing switch on a busbar section can be closed at a time.

The earthing resistance on the alternator limits the earth current to 1 500 amperes at 6 350 volts and on the transformers to 200 amperes at 19 000 volts.

A general view of the control room is given in Fig. 9 (see Plate 2).

Main Switchgear

The whole of the main switchgear controlling the three 36 500-kVA and three 62 500-kVA alternators, and 19 outgoing feeders, is of the cellular type, housed in stoneware cubicles.

It was originally intended to run the main busbars in three sections, but owing to the late introduction of larger machines and to the grid connections it has been found necessary to sectionalize the transfer busbars in addition and to couple all 6 sections to a tie-bar through reactors as shown diagrammatically in Fig. 10. Normally the centre bus-section switches are closed and the system is operated in three sections with two alternators feeding each section, or, alternatively, in six sections with one alternator feeding each section.

The cubicles are so constructed that the three phases of each circuit are completely isolated; the through bushing insulators connecting the compartments are of porcelain bushed with mica.

The tie-bar reactors installed are wound on concrete formers having a normal full-load current of 2 000 amperes and a reactance per phase of $7\frac{1}{2}$ %, thus giving 2 850 kVA per 3-phase bank at 11 000 volts.

The busbars are completely insulated with micanite tested to 22-kV, supported at about 3-ft. centres on compression-type insulators.

All circuit-breakers are solenoid electrically operated and (with the exception of those controlling No. 6 alternator and associated switchgear, which are rated at 1 million kVA) have a rupturing capacity of 750 000 kVA.

The 1 000 000-kVA breakers have a rated making current of 132 000 amperes and a breaking current of 52 000 amperes at 11 000 volts.

All main switchgear is remotely controlled and alternator protection is by McColl biased-beam type, 3-phase circulating-current relays. Similar protection is fitted to each of the 6 reactor banks.

The main switch contacts open at a velocity of 5–6 ft. per sec., when the voltage of the 220-volt d.c. operating circuit falls to 90 volts.

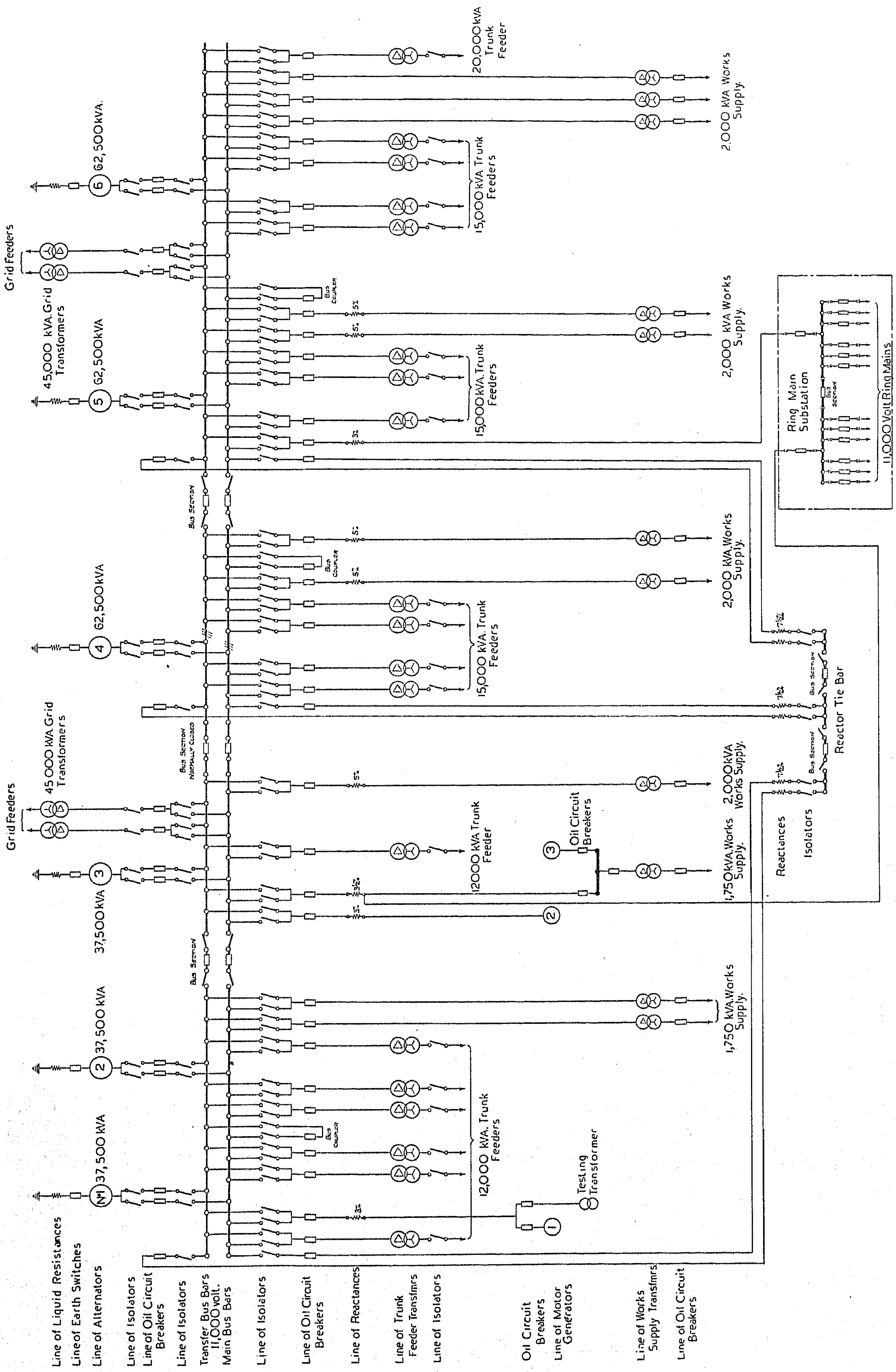

Fig. 10.—Main-busbar diagram (11 000 volts, 3-phase, 50 cycles per sec.).

The maximum current density of the main and duplicate busbars does not exceed 700 amperes per sq. in. for copper strips with air spaces, 600 amperes per sq. in. for solid circular rods, and 50 amperes per sq. in. for bolted joints and fuse contacts.

The arrangement of the main alternator and outgoing circuits is shown diagrammatically in Fig. 10.

Main Transformers

All transmission is at 33 000 volts and 19 step-up transformers are installed, 7 of 12 000 kVA, 11 of 15 000 kVA, and one of 20 000 kVA, all fitted with on-load tap-changing gear to give a voltage control of $\pm 7\frac{1}{2}$ % in 10 steps. The tap-changing equipment is electrically remote-controlled.

Technical particulars of the transformers are given in Table 14 (see Appendix).

PART 2.—OPERATION

Feed-Water Treatment

The control of feed-water treatment is not part of the duties of the operating staff, but is in charge of a separate testing department.

Daily water samples are taken:—

(1) From each boiler drum.
(2) Of boiler feed-water from each of three feed pumps.
(3) Of untreated water entering storage reservoir.
(4) Of untreated water leaving reservoir.
(5) Of softened make-up water leaving Zeolite plant.
(6) Of untreated condensate.
(7) Of treated condensate.
(8) Of condenser circulating water (sewage effluent).

The boiler feed-water is conditioned by admitting, by hand adjustment to each condensate discharge, a small amount of soda ash in quantities dependent upon the state of the condensate and the amount of condenser leakage as determined by conductivity tests made with a Dionic water tester. Under normal operating conditions the conductivity of the untreated condensate varies between about 4 and 8 degrees; readings much in excess of these figures are indicative of condenser leakage and demand inspection of the condenser tubes and packings. Automatic conductivity meters are now being installed to facilitate the conditioning of the condensate and to detect excessive condenser leakage.

To prevent scale, corrosion, and priming, the concentration of dissolved solids in the boiler water is maintained as low as possible consistent with economic operation, and is normally between 40 and 60 grains per gallon. A continuous system of boiler blow-down is now under consideration whereby the maintenance of satisfactory water conditions in the boiler drums will be almost automatic.

The amount of water blown down varies from 1 % to 1·5 % of the total water evaporated.

Owing to the use of sewage effluent as circulating water, condenser leakage can have a serious effect on boiler operation, giving rise to wasting and pitting of the steel surfaces in the boiler and to scale formation, particularly on surfaces subjected to high rates of heat transference, whilst organic matter can accentuate priming and foaming.

The influence of the water condition in the boiler drum on priming is complex, and whilst it is obvious that the lower the concentration the less likelihood of priming, yet fluctuating operating conditions and high water levels in the steam water drums may cause priming even with low concentrations.

The prevention of scale in boiler tubes is largely a question of correct water treatment, but boiler design is also important. A free and positive water circulation, the absence of settlement pockets, and the avoidance of flame impingement on tube surfaces and high localized rates of transmission, all assist in the prevention of scale.

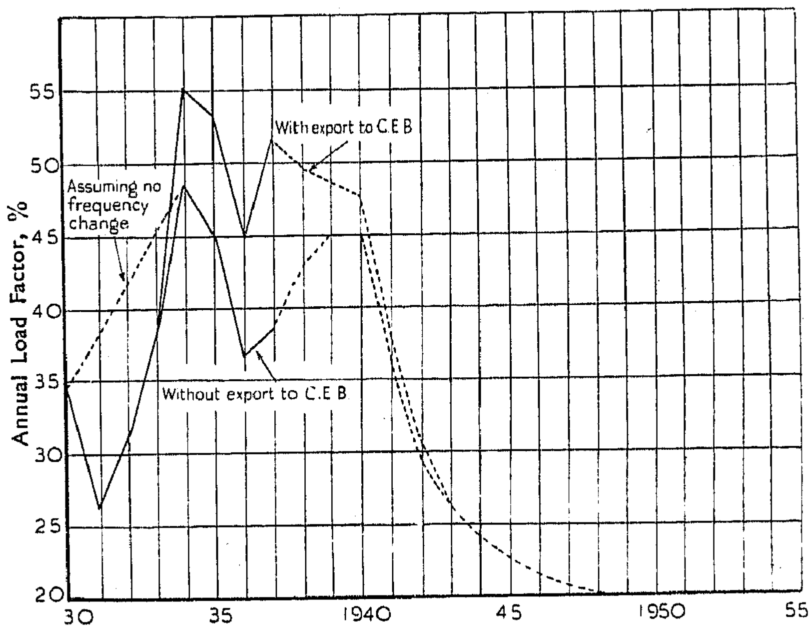

Fig. 11.—Average load factor, 1930–55:—

(*a*) With frequency-change and export to C.E.B. (actual condition), 31·77 %.
(*b*) With no frequency-change and with no export to C.E.B., 30·47 %.
(*c*) With frequency-change and with no export to C.E.B., 29·76 %.
(*d*) With no frequency-change and with export to C.E.B., 32·49 %.

Estimated - - - - - - - - - - - - - - - - - Actual ————————

In practice the oxygen content in the boiler feed-water does not exceed 0·1 millilitre per litre, whilst the oxygen content of the condensate leaving the condenser does not exceed 0·03 to 0·05 millilitre per litre. De-aerators are not used in the water circuit.

Heat-Cycle Analysis

For a new station a load factor of 30 %, which was chosen for Hams Hall in 1926, may seem too low and it may therefore pay us to investigate the accuracy of this early choice in the light of subsequent events.

The actual load-factor variation of Hams Hall with and without export units to the Central Electricity Board up to December, 1937, is shown in Fig. 11. From this date onwards to December, 1955, when all loan charges will cease, the load factor has been estimated.

The basis of this estimate of average load factor shown in Fig. 11 is the assumption that the first section of the proposed new station, to be known as Hams Hall " B,"

will be in commission in 1940 and thereafter be extended and operated as a base-load station.

The average load factor given by the lower curve is 29·76 %, whilst the highest average, including Board export and neglecting lost output due to frequency-change conditions, is 32·49 %.

Turning to other stations, we find from the Electricity Commissioners' returns that the average load factor over a period of 12 years at Dunston "A" station is 35·95 %, at Carville "B" 43·04 %, and at Nechells Princes station 30·26 %. All these stations have been supplemented in middle life by more modern plants.

One of the highest average load factors recorded is 53·2 % at Kearsley "A" station over a period of 8 years.

It is therefore reasonable to suppose that under favourable conditions extending over a period of, say, 25 years,

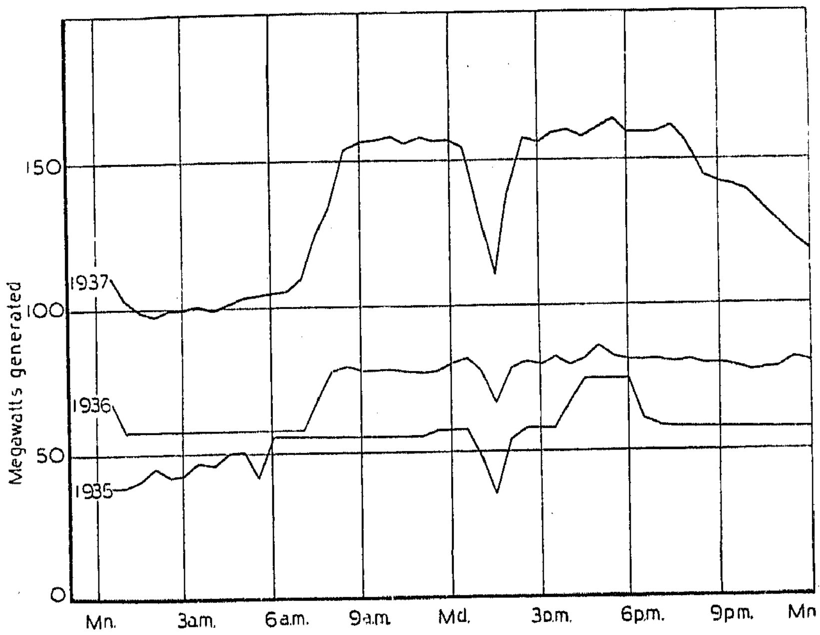

Fig. 12.—Typical winter load curves.

the average load factor of most new power stations is not likely to exceed 40 %, assuming load growth to continue at the present rate, and to design a station for a higher load factor would appear to be economically unsound.

The analysis of operating results presents many difficulties as there are so many variables. For example, the shape of the average daily load curve affects operating efficiency.

Figs. 12 and 13 show typical winter and summer load curves for Hams Hall station, the load changes varying from 2·5 to 1 between 1935 and 1937, the latter year being the least favourable. Fig. 14 shows curves of maximum demands and plant capacity.

The average Willans line as shown in Fig. 15 is almost useless for the purpose of analysis, as it does not give a comparison between actual and ideal operating conditions, nor does it give the correct stand-by losses as the zero point is obviously incorrect.

In practice the capacity of Hams Hall has grown from 60 000 kW in 1930 to 240 000 kW in 1938, hence the operating results obtained between these dates must be referred to plant capacity.

Fig. 16 shows the calculated ideal Willans lines for all 6 generating units added together to form a basis of comparison, with lines drawn through points representing actual operating results; these points show well-defined steps as each machine comes into operation.

The vertical distances between the ideal and actual Willans lines fairly represent the heat losses due to operation, and when averaged can be used as a measure of the operating efficiency in terms of ideal performance.

An important relation is established in Fig. 17, which shows the variation of operating efficiency with growth and use of plant capacity, and this can be regarded as the characteristic of the power station or its reaction to external conditions. This curve is derived from Fig. 16 and represents the average ratio of theoretical to actual heat consumption for any given plant capacity over its operating range.

For those who wish to examine the actual operating statistics, Table 15 has been prepared (see Appendix).

It has already been suggested that a power station should be designed to suit its environment, and the aim of this Section of the paper has been to examine whether Hams Hall has been so designed and at the same time to

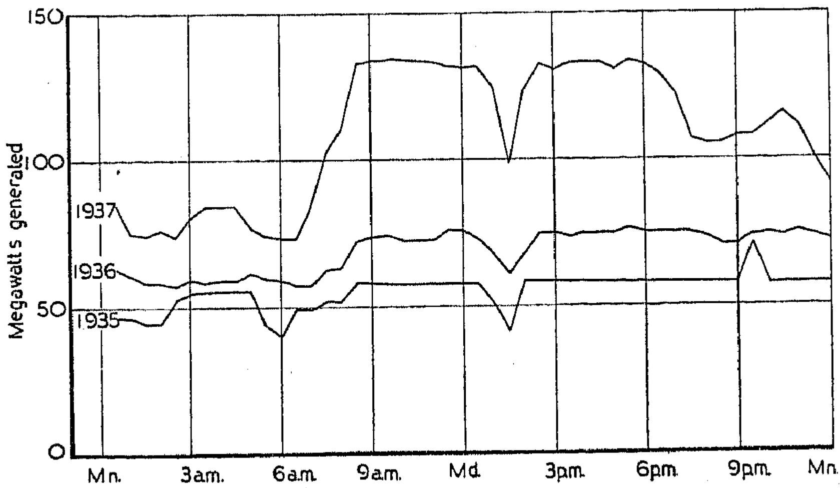

Fig. 13.—Typical summer load curves.

suggest a method of analysis that could be applied to other power stations.

Coal-Handling Plant

The coal-handling plant, designed for an average load factor of 30 %, could under such conditions be operated by one shift of men or at the most two shifts during the winter months.

The load factor having temporarily increased to 60 %, 3 shifts became necessary, each requiring 4 men on tippler operation and one for shuttle-belt operation. One spare shift of 5 men is also essential for continuous operation of the entire plant.

All coal from the tipplers to hoppers passes through 2-in. square-mesh grids.

The performance of each coal-handling plant is given in Table 16 (see Appendix).

Pulverizing Plant

The total mill equipment consists of 40 mills; the first 25 are gear-driven and require oil replacement every 1 200 hours, and the second 15 are direct motor-driven units.

Only one mill attendant per shift is required. He

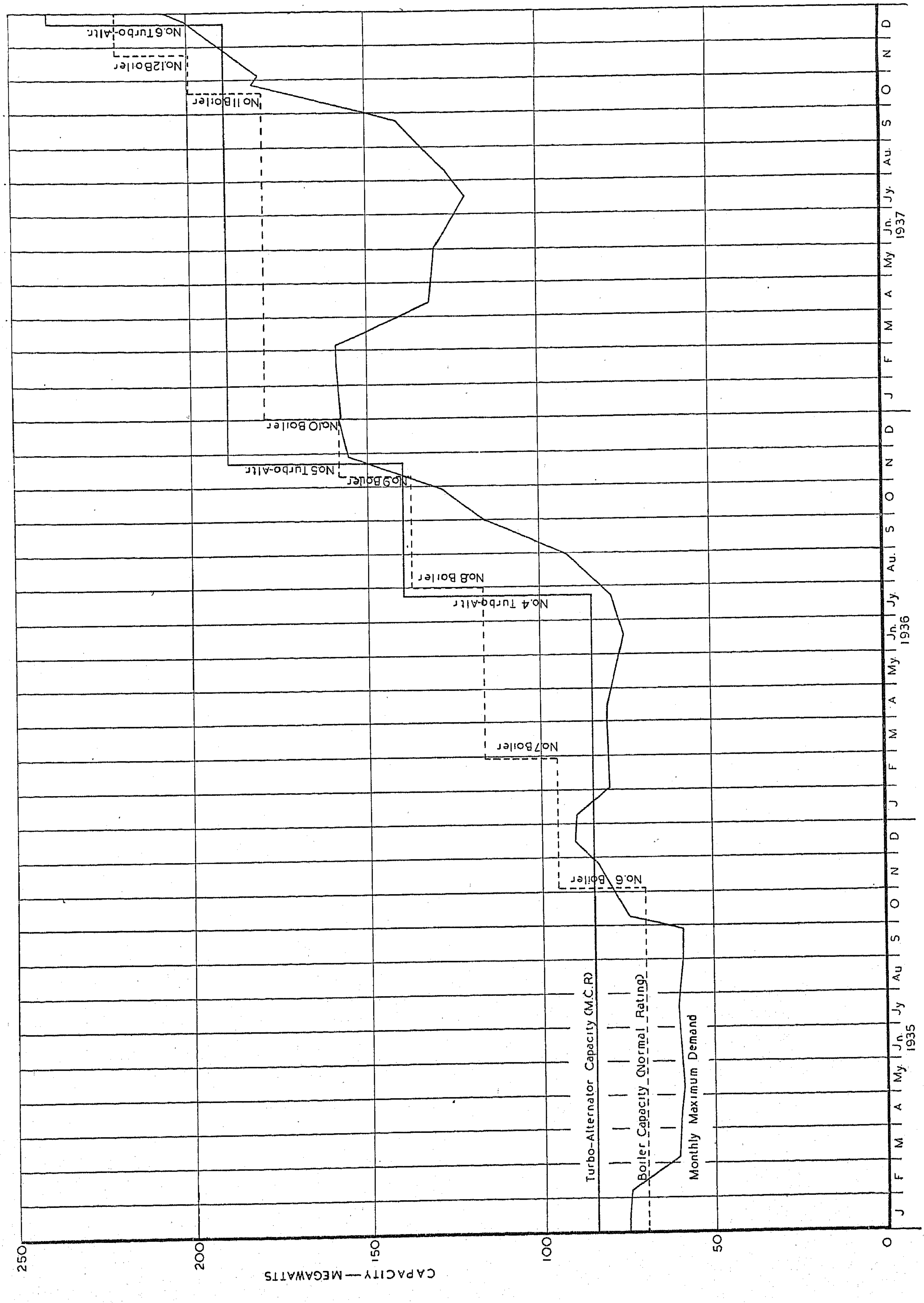

Fig. 14.—Monthly maximum demands and plant capacity.

patrols the mill floor and takes ammeter readings, supervises oil supply to mills, clears chokes, operates dampers, and starts up and shuts down mills as directed.

Magnetic separators are fitted on the coal belts and also on the feeder tables.

Sampling for fineness of the pulverized-fuel product is by means of the insertion of a $\frac{3}{4}$-in. bore pipe in the coal-air stream connected to a linen bag for reception of the sample. The average degree of fineness is 85 % through a 100 I.M.M. square-mesh sieve, the life of the wearing parts of the mill being about 1 600 hours.

The average performance of the mills over a long period and a total pulverization of 2 million tons of fuel is given below:—

Average type of fuel used:—

(*a*) Screenings over $\frac{1}{2}$ in. ..	25·9 %
(*b*) Fine slack	74·1 %
Average total moisture content	13·4 %
Number of running hours ..	853 503
Average load on mill ..	2·35 tons/hour
Power consumed per ton ..	24 kWh

Ash-Handling Plant

The heavy ash, which is water-sluiced by gravity trough from the ash hoppers to the settling sumps, can be used for road-making, and much of this is removed from the site by private haulers free of cost.

This plant is operated on 2 shifts, 3 men per shift, i.e. telpher driver, petrol-loco driver, and one labourer.

The fine ash is much more difficult to handle and dispose of than is the heavy ash, a total of 12 men on a 4-cycle rotating shift being necessary to operate and control the sluice system, the filter plant, and the loading of standard-gauge trucks with the final product—fine ash with about 20 % moisture, a condition which depends on the nature of the fine dust.

The finer the dust the more difficult it is to obtain a suitable product. Fine dust tends to produce a slurry liable to choke the chutes rather than a "cake" which is easy to handle.

Attention to pipe-lines to prevent choking with settled ash is necessary, and frequent flushing with water is essential.

Daily purging of the circulating-water system is necessary to prevent insoluble salts from forming and encrusting the pipe lines.

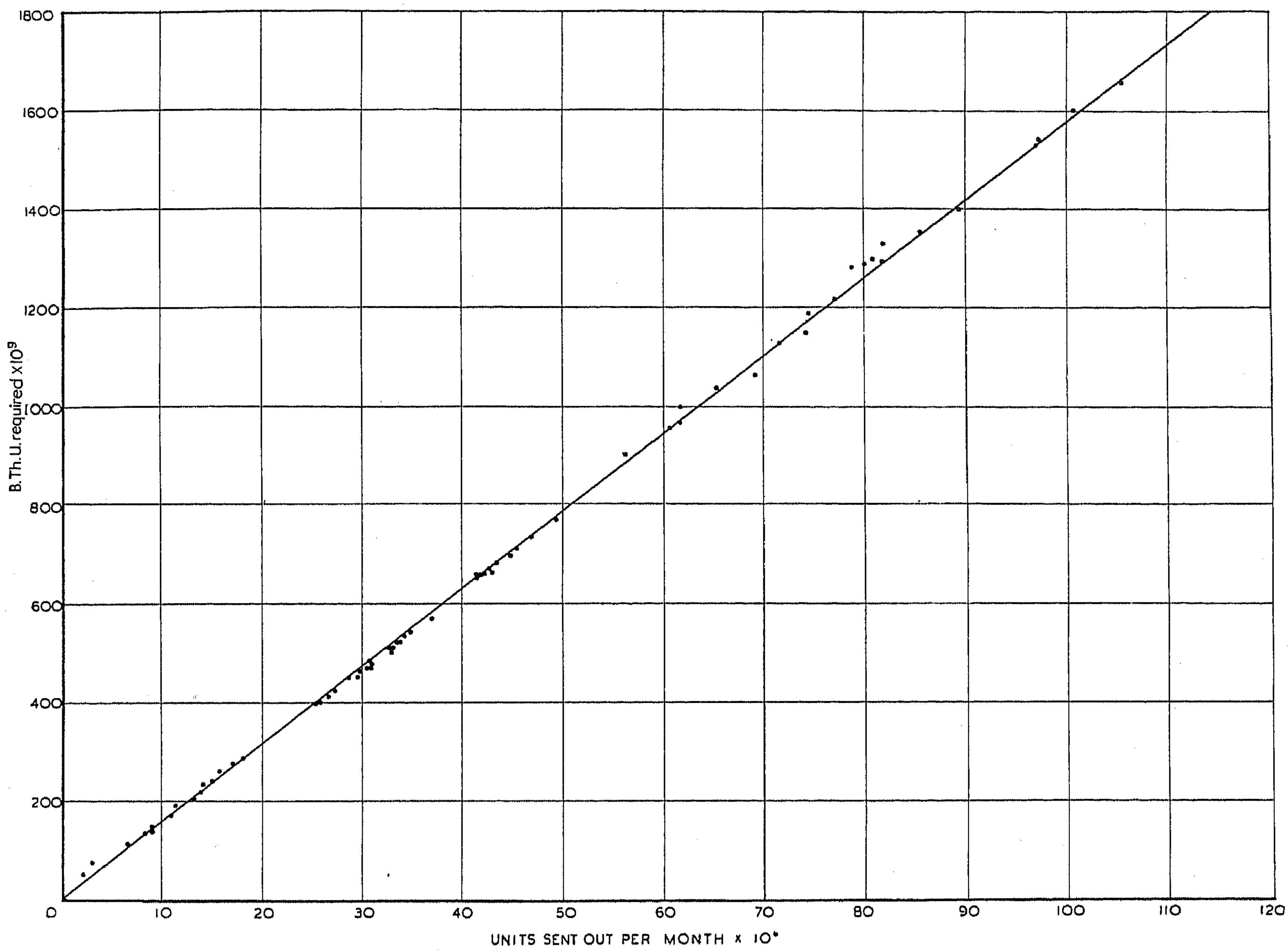

Fig. 15.—Average Willans line (based on actual operating statistics).

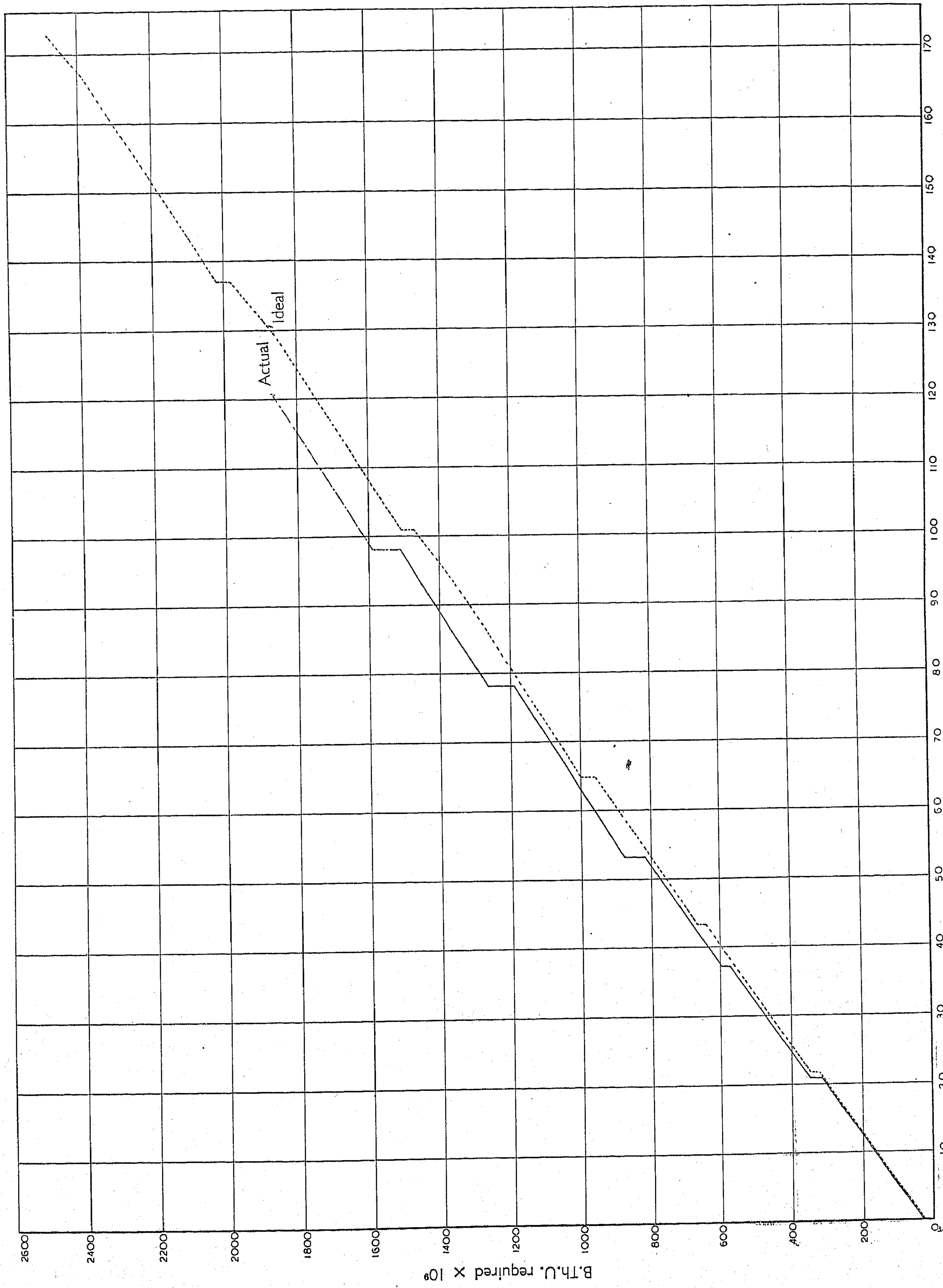

Fig. 16.—Ideal and actual Willans lines.

The disposal of the ash on site requires one shift of 6 men to control the petrol-driven excavators and dumpers.

Electro-Filter Plant

As it is probable that the design and construction of electro-filter plants may form the subject of a separate paper in the near future, it is not proposed to deal with this matter in detail.

It may, however, be of interest to record that observations of chimney emission have been carefully carried out in the vicinity of Hams Hall for many months and it has been established that the dust fall is less than in many other large cities. To attempt a more precise statement would be misleading, having regard to the number of variables involved, such as boiler load, ash content in the fuel, wind velocity, and humidity.

As regards the fine dust as collected, the density of which at 15·5° C. is about 2·12, the average percentage fineness above 25 microns being about 16 % and loss on ignition about 5 %, there is a possibility that a market may be found for this by-product in the near future. In this event, dry-dust collection would be necessary.

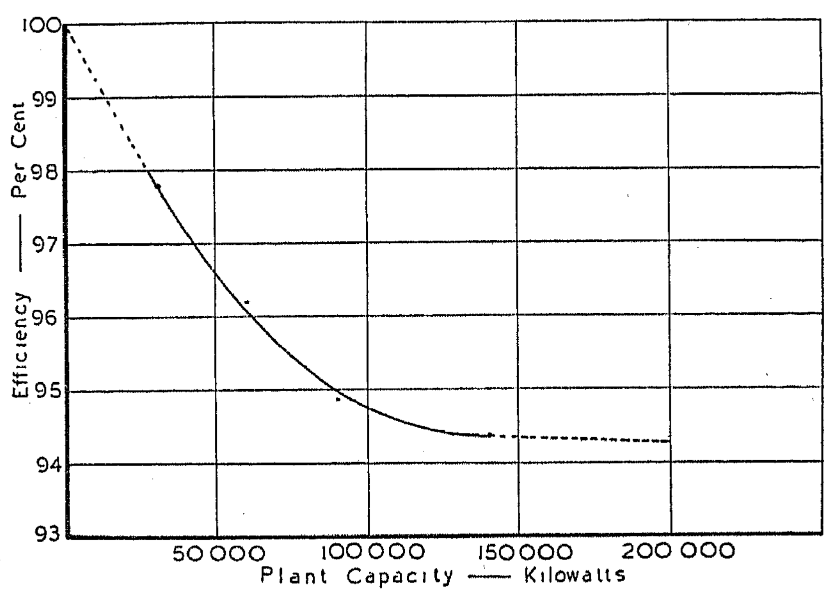

Fig. 17.—Operating-efficiency curve.

Boiler Plant

The straight-tube boilers fired with pulverized fuel with an average ash content of about 7 % require cleaning after 600 hours' steaming, and with fuels of about 18 % ash this period is reduced to about 350 hours; birds-nesting takes place in the first few rows of tubes.

The bent-tube boilers fired with pulverized fuel do not so rapidly get choked, and usually 1 500 steaming hours between cleanings is practicable with heavy-ash-content low-grade fuels.

The stoker-fired boilers require cleaner fuels with a coking index not lower than $4\frac{1}{2}$.

In these boilers choking of the superheater first takes place, and cleaning after 750 hours is usually necessary.

Generally, the pulverized-fuel-fired boilers can be brought up to pressure from cold in $1\frac{1}{2}$ hours, 5 to 6 tons of fuel being required; whilst the stoker-fired units can be under steam in from 2–$2\frac{1}{2}$ hours, about 10 tons of coal being necessary.

The stokers' duties are practically confined to the firing floor. These men work on a 4-cycle rotating shift; one stoker operates two boilers, and a leading stoker whose duties are supervisory is on shift.

The performance of the boiler units is given in Table 17 (see Appendix).

Turbo-Alternators

In the turbine room a 4-cycle shift of drivers is employed; a leading driver with supervisory duties controls 6 turbo-alternators and 6 qualified drivers.

Oil samples are taken daily from each machine, and a complete oil analysis is made every 2 months.

A centrifugal oil purifier is fitted in the oil circuit of each machine. All make-up oil, amounting to 285 gallons per set per annum, is tested before use to fulfil satisfactorily the following requirements:—

Flash point	356° F.
Volatility	0·5 %
Acid value	0·1
Copper discoloration ..	None
Emulsification number ..	2

All protective relays are tested every 3 months, and the switchgear is inspected and tested every 6 months at 23 000 volts (d.c.) to earth.

The performance of the turbo-alternators is given in Table 18 (see Appendix).

Cooling Towers

The correct size of cooling tower for any given conditions is a matter of some importance and one not easily determined, so many are the variables concerned.

It is impracticable in the space available to deal with this subject in the present paper; the barest outline must therefore suffice.

Having first ascertained the heat to be dissipated in the condenser under vacua varying from, say, 28 to 29 in. Hg, our problems are to decide:—

(*a*) The most economic vacuum.
(*b*) The quantity of circulating water to be used.
(*c*) The heat-load for which the towers must be designed.
(*d*) The average atmospheric conditions.

It will be found that the condenser design and the cooling-tower size are so fundamentally related that it is impossible to decide on one without reference to the other.

For every change in conditions a new set of calculations must be made afresh, and only by laborious and painstaking effort can an economic solution be reached.

For example, under atmospheric conditions of, say, 60° F. dry-bulb temperature, cooling towers for a vacuum of 29 in. Hg would be impracticable.

The cooling towers at Hams Hall were designed for a vacuum of 28 in. Hg with average atmospheric conditions of 60° F. (dry-bulb temperature) and 70 % humidity, necessitating a flow of 31 500 gallons of circulating water

per minute for each 50 000-kW machine operating at maximum rating under feed-heating conditions.

At an economic rating of 40 000 kW when feed-heating, the vacuum obtained is about 28·25 in. Hg. These conditions are about the economic limit for an average station load factor of about 30 %.

This problem was again reviewed for the new station and it may be interesting to record that with a station load factor of 40 % under similar atmospheric conditions, the economic vacuum is 28·5-in. Hg when each 50 000-kW machine is developing 40 000 kW under feed-heating conditions and when supplied with steam at 650 lb. pressure and 845° F.

Table 2

Average Cost of Coal Handling

Description	Cost per ton of coal handled	
	From tipplers to bunkers	From tipplers to coal store
	d.	d.
Operating labour	1·95	5·35
Repairs and maintenance ..	1·81	1·00
Power at 0·15d. per unit ..	0·035	0·024
Total	3·795	6·374

From the evidence available it appears that an average vacuum of 28·5 in. Hg is about the economic limit for the conditions considered, for even a further increase of 0·25 in. Hg nearly doubles the cooling-tower capacity required, assuming that 75° F. may be taken as a reasonable outlet-water temperature from the cooling system.

A summary of the test-results taken on one of the cooling towers is given in Table 19 (see Appendix).

Table 3

Average Coal-Pulverizing Costs, Based on a Total of 2 Million Tons Pulverized

Description	Average cost per ton pulverized
	d.
Operating labour	0·64
Repairs and maintenance (materials) ..	2·88
Repairs and maintenance (labour) ..	0·60
Miscellaneous stores	1·08
Power at 0·15d. per unit	3·60
Total	8·80

Main and Auxiliary Switchgear

All switching and control operations are carried out on a 4-cycle rotating-shift system.

In the control room a junior engineer and switchman are employed, whilst on the works an electrician is in charge of maintenance and cleaning work on generators and motors.

Table 4

Average Cost of Ash-Handling

Description	Cost per ton of ash handled	
	Rough ash and stoker ash	Fine dust
	d.	d.
Operating labour	5·15	8·16
Repairs and maintenance ..	4·02	4·47
Power at 0·15d. per unit ..	0·24	1·05
Transport costs to tip	4·35*	4·35*
Operating labour on dumpers ..	4·80*	4·80*
Repairs and maintenance on dumpers	4·82*	4·82*
Petrol used by dumpers ..	2·53*	2·53*
Total	25·91	30·18

* These items of cost are not incurred for ash taken from site by private haulers.

All major repairs and electrical testing are carried out by an electrical maintenance staff.

Trunk feeder switches are inspected and adjusted every 6 months and then tested to 23 000-volts (d.c.) between phases and earth.

Overload relays are adjustable between 0–2 sec., the general setting being—motor-generators 150 % full load, 0·5 sec.; works supply transformers 200 % full load, 1·0 sec.; trunk feeders 200 % full load, 1·5 sec.

Table 5

Cost of Water Treatment per Unit Sent Out*

Water-softening plant	Cost per unit sent out, pence	
Salt	0·00001369	
Water used in washing-out brine	0·00001369	
		0·00002738
Boiler feed-water conditioning		
Soda ash	0·0000183	
Caustic soda	0·00000413	
Sodium phosphate† ..	0·00000076	
		0·00002319
Repairs and maintenance		
Material	0·0000126	
Labour	0·0000274	
		0·00004
Wages of plant attendant	0·0000417	0·0000417
Total		0·00013227
		(say 0·000132)

* In this Table the costs have been worked out for a period of 12 months ending 31st March, 1938, with the exception of the item for "Repairs and maintenance." In this case the expenditure varies so much from year to year that an average figure for 12 months based on the last 5 years' working has been included.

† An initial charge of sodium phosphate is put into the drum of each new boiler and on any subsequent occasion when a boiler is completely emptied.

The second section of the station is equipped with induction-type relays instead of the biased-beam type, as the latter are affected by vibration.

During the last two years, the protective gear has operated as follows:—

11 000-volt ring mains ..	Overload relays	15 times
11 000-volt a.c./440-volt d.c. motor-generators (works supply)	Overload relays	Twice
33 000-volt trunk feeders ..	Earth leakage	5 times

Table 6

TOTAL WORKS COST

	Cost per unit sent out, pence					
	1935		1936		1937	
Coal	0·0795		0·1012		0·1219	
Coal and ash-handling	0·0077		0·0076		0·0098	
		0·0872		0·1088		0·1317
Oil, water, and stores	0·0019		0·0025		0·0026	
Salaries and wages	0·0083		0·0070		0·0067	
Repairs and maintenance	0·0091		0·0090		0·0072	
		0·0193		0·0185		0·0165
Total works cost		0·1065		0·1273		0·1482
Coal cost per ton	9s. $6\frac{3}{4}$d.		11s. $11\frac{1}{4}$d.		14s. $4\frac{3}{4}$d.	
Load factor	53·2 %		44·6 %		51·6 %	

Table 7

CAPITAL COSTS

	Generation		Distribution	
	Total cost	Cost per kW*	Total cost	Cost per kW*
	£	£	£	£
Land	23 250	0·093		
Buildings	579 646	2·324	60 000	0·241
Turbo-alternators, condensing plant, etc. ..	801 150	3·212		
Cooling towers, effluent pumps, etc.	404 925	1·623		
House sets, motor-generators, battery, and works transformers	54 131	0·217		
Boilers and auxiliary plant	1 029 190	4·126		
Coal-, ash-, and dust-handling, and railway sidings	328 025	1·315		
Steam and water pipes	77 385	0·310		
Workshop and upkeep equipment	17 760	0·071		
Switchgear	193 084	0·774	116 944	0·469
Main transformers			128 842	0·516
Station cables	98 848	0·396		
Wiring and lighting	18 437	0·074		
Sundries	2 071	0·008	1 000	0·004
	3 627 902	14·543	306 786	1·230
Electro-filter plant				
Electro-filter plant (including buildings) ..	73 768	0·296		
Brick chimneys	40 533	0·162		
Ducting from boilers to chimneys	43 545	0·176		
Dust-disposal plant	37 992	0·152		
Total	3 823 740	15·329	306 786	1·230

* Based on gross generator capacity of 249 450 kW.

The operation of the protective gear is checked every 3 months by applying a test current to the primary of the current transformer.

Personnel

At Hams Hall some attempt has been made to approach general efficiency by instituting vocational training in the manual grades, followed by proficiency tests leading to promotion and the award of a certificate of merit to successful candidates.

The reasons behind these vocational tests are that skilled men are essential to the proper operation of modern plants and further, in practice, proficiency lends to the individual that pride of achievement and keenness so necessary for the personal satisfaction of the individual with his duties. A high standard of proficiency makes these duties important and therefore worth while.

It has indeed been made possible for manual employees of exceptional ability who have the necessary technical qualifications—the Higher National Certificate awarded jointly by the Board of Education and The Institution —to be promoted to staff positions.

Table 8

PRODUCTION COSTS

Description	Total production costs per unit sent out		
	1935	1936	1937
	d.	d.	d.
Total works costs from Table 6	0·1065	0·1273	0·1482
Overhead charges ..	0·0851	0·0797	0·0699
Total production costs ..	0·1916	0·2070	0·2181

Staff recruitment is usually, however, from engineering or student trainees who have had the benefits of a more generous general and technical education with practical engineering works training.

The designer should have some regard for the well-being of the operators; simple symmetrical and orderly layout assists cleanliness, uniform and easy slopes on all stairways add to ease of work, and uniform arrangement of plant details eliminates many operating mistakes.

There is, moreover, no sufficient reason why the external surroundings of power stations should be drab, ugly, or untidy. Dirt is no asset; it is not even cheap, it corrodes the plant, it is depressing, and it obliterates that most precious of all personal attributes in the operators —self-respect.

PART 3.—COSTS

The more carefully we analyse power production costs the more difficulties do we find in accurately comparing in detail the financial results of one power station with those of another. We may approximate for coal price-quality difference, also variations in heat cycle, but charges directly or indirectly due to local conditions for the most part elude us. Apart from coal price-quality and heat cycle, the operating charges incurred at Hams Hall that are most influenced by local conditions are those attributable to coal-, ash-, and dust-handling, and water treatment. These costs are given in Tables 2, 3, 4, and 5, to aid comparison with other dissimilar plants. The total works costs are given in Table 6, and the capital costs in Table 7.

During the last 3 years' operation at Hams Hall the average coal price per ton has risen by 50·54 % and the coal price per B.Th.U. by 49·34 %, whilst over the same period the total cost of production has risen by 13·83 % and the load factor has fallen from 53·2 % to 51·6 %.

The total production costs at Hams Hall during 1937, using low-grade fuels as in 1935 at 9s. 6¾d. per ton, would have been 0·1778d. per unit sent out.

The cost of this increase in coal price per B.Th.U. would have been £152 775 for the output in 1937, and the coal price still continues to increase.

Table 8 shows the total production costs at Hams Hall for 3 years, each ended December 31st, as agreed with the Central Electricity Board.

CONCLUSIONS

So grave is the lack of unity in a paper written about power stations, and so diverse are the subjects which must be included, that to reduce chaos to order we can scarcely resist the attempt to generalize, although we know that but few generalizations can be strictly true.

To-day it is orthodox to worship at the shrine of financial economy and to abandon the altruistic and heroic cult of thermal efficiency, yet should coal conservation become essential these ideals would be sharply reversed.

We have seen how necessary it is to establish an economic frame of reference based on local conditions, how important the determination of average load factor can be, and what operating efficiency is likely under actual conditions.

Operating experience has shown the importance of a high and uniform degree of fineness of coal pulverization, and has shown that with electro-filter plants and tall chimneys dust emission is reduced and dispersed, whilst sulphur emission is but slightly affected.

It has also been observed that the performance of cooling towers and of condensing plants is intimately associated and that with modern heat cycles an average vacuum of 28·5-in. Hg may be justified. Heat-cycle analysis has shown the variation between hypothetical and actual operating conditions, the influence of plant capacity allied with load conditions on operating efficiency, and the inadaptibility of average Willans lines for such analysis.

It is reasonable to inquire which features of Hams Hall station would be repeated and which rejected in a new station to be constructed in the same locality.

Identical conditions can rarely be repeated in practice after a lapse of time, even in one locality. A good example of changed conditions on selection is the proposed design of Hams Hall "B" station to be constructed shortly on a site adjacent to the present plant.

Twelve years separate the designs of the two stations, and during this time coal prices have increased, high-

voltage generation has become established, and higher steam temperatures are now practicable. All these changes call for modifications in design.

As regards layout, the simplicity and uniformity of the existing station will be repeated—a single row of boilers parallel to a single end-on row of turbo-alternators. Electrostatic flue-gas-cleaning plant will be retained, but differently arranged, and 4 instead of 6 ferro-concrete cooling towers are proposed.

The absence of architectural adornment of the new buildings will be more rigorously enforced, and the use of ferro-concrete instead of structural steel for the superstructure is proposed for economic reasons.

The absence of roof lights and of external windows to basements is a condition imposed by air raid precautions, as is also the construction of switch-houses and control rooms remote from the main buildings.

The maximum coal traffic is estimated to be 8 000 tons daily, and, to cope with this volume of traffic, sidings to accommodate 3 days' supply instead of one become necessary to avoid main-line congestion.

Pulverized-fuel firing using large boilers of 320 000 lb. per hour evaporative capacity is estimated to save on the new station (of 300 000 kW output) some £40 000 per annum when compared with stoker firing, notwithstanding the cost and upkeep of electrostatic flue-gas-cleaning plant and the consequent ash- and dust-handling.

Belt conveyors will be repeated at the new station, but a circular coal store is proposed which, it is estimated, will effect considerable saving on the cost of reclaiming as compared with the present scheme.

The present design of grit- and dust-handling plant will not be repeated; a newer scheme is proposed where the dust is wetted at a much reduced capital outlay and operating cost than at present.

For the higher steam conditions of 650 lb. per sq. in. pressure and 845° F. total temperature, evaporators are proposed, together with 4 instead of 3 stages of feed-heating; a similar arrangement of feed and circulating-water pumps will be repeated in the new station.

Turbo-alternators of 50 000 kW output will again be used in the new station, but 33 000-volt instead of 11 000-volt generation is proposed.

For steam pipes welded joints will again be used and, where possible, plain instead of corrugated expansion bends are proposed.

In the new station separate steam-driven house generators are not proposed. Alternating-current generators coupled direct to the main alternator shafts will be used, as on the three later machines installed in Hams Hall.

The new control room will not be a long narrow room in the switch-house block, but a separate circular room situated at some distance from the main building. The main switchgear will also be housed remote from the main building in 6 separate rooms, one associated with each alternator and its group of outgoing feeders. All switching and transmission will be at 33 kV instead of 11-kV, thus eliminating step-up transformers.

The new station is planned in two sections—three machines in each section—better to enable two separate heat cycles to be adopted in the same building if desired.

It will thus be seen that but three fundamental features remain constant for both stations—the character of local fuels, the use of sewage effluent for condenser circulating water with cooling towers, and site location.

If, therefore, conditions can vary so much between two stations constructed in the same locality during so short a time, accurate comparison between production costs of two entirely dissimilar stations is impossible without the closest reference to external and local conditions which prevailed at the time of design and during operation.

Moreover, whilst a power station is one composite machine when completed, it grows but slowly in size and output, at length to diminish yearly in generation as obsolescence approaches.

A true understanding of what is real economy is obscured by the ever-changing technology of power production, by the difficulties of accurately forecasting operating conditions many years ahead, and by reactions of local trade developments.

We have seen that an economic frame of reference, so easy to describe, is difficult to construct. Our problem is to avoid confusing this simple fabric with a tangled web of opinions which are at best poor substitutes for knowledge.

For a definition of economy we may do worse than quote Edmund Burke, who says:—

> "Economy is a distributive virtue, and consists not in saving but in selection; parsimony requires no providence, no sagacity, no power of combination, no judgment."

ACKNOWLEDGMENTS

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APPENDIX

Table 9

TECHNICAL PARTICULARS OF COAL-HANDLING PLANT

	Inclined conveyor	Bucket elevator	Horizontal conveyor	Shuttle belt
Number per set of coal-handling plant	2	2	1	2
Capacity of each conveyor or elevator, tons/hour	100	100	100	100
Belt or bucket speed—feet per minute	480	50	350	565
Width of belt or bucket capacity	20 in.	152 lb.	20 in.	20 in.
Length of belt or number of buckets	416 ft.	76 bkts.	930 ft.	226½ ft.
Inclination of belt conveyor	20°	—	—	—
Rated h.p. of 400-volt driving motors	17½	17½ or 20	10	5

Wagon Tipplers (Two per set of coal-handling plant):—

Capacity of each tippler	100 tons/hour
Suitable for 8-, 12-, and 20-ton wagons	
Rated b.p.h. of driving motor	25

Jib Cranes (Steam-driven—one per set of coal-handling plant):—

Capacity of crane	100 tons/hour
Capacity of grab	90–130 cu. ft.
Length of jib	72 ft.
Working radius of jib	27–60 ft.
Rated b.h.p. of main driving engine	90
Rated b.h.p. of auxiliary driving engine	30

Table 10

TECHNICAL PARTICULARS OF BOILER PLANT

Item	Description	First section 1929	Second section 1934–36	Third section 1936–39
1	Number of boilers	5	3	6
2	Continuous evaporative capacity, lb./hour	180 000	250 000	250 000
3	Type of boiler	Straight tube	Bent tube	Bent tube
4	Method of firing	Pulverized fuel (impact)	Pulverized fuel (impact)	Chain-grate stoker
5	Number of pulverizers per boiler unit	5	5	—
6	Maximum capacity of each pulverizer with fuel having 25 % total moisture content, tons/hour	4	5·15	—
7	Fineness of pulverized fuel through 100 mesh, %	83	82	—
8	Preheated-air temperature to boiler, ° F.	445	445	272
9	Heating surface (each boiler), sq. ft.:—			
	(*a*) Combustion chamber and water screen	2 490	6 230	2 376
	(*b*) Boiler	20 000	20 310	23 780
	(*c*) Superheater	4 566	7 050	5 500
	(*d*) Economizer	—	—	12 960
	(*e*) Air heater	40 800	48 960	21 870
10	Total heating surface, sq. ft.	67 856	82 550	66 486
11	Feed-water temperature, ° F.	295	300	300
12	Total steam temperature at superheater outlet, ° F.	710	730	730
13	Steam pressure at superheater outlet, lb./sq. in. (gauge)	375	375	375
14	Superheater variation between 0·5 and 1·0 load, deg. F.	35	45	47
15	Exit flue-gas temperature, ° F.	295	295	320
16	CO_2 in exit flue gas, %	14	14	12·5
17	Area of each chain-grate stoker, sq. ft.	—	—	620
18	Coal-burning rate with coal at 12 000 B.Th.U./lb. (lb./sq. ft./hour)	—	—	53·8
19	Number of induced-draught fans (per boiler)	2	2	2
20	Number of forced-draught fans (per boiler)	1	2	2
21	Number of secondary air fans (per boiler)	—	—	2
22	Type of mechanical dust arresters	Cyclone	Cyclone	Cyclone

Table 11

TECHNICAL PERFORMANCE OF PLANT

Item	Description	First three sets, 30 000 kW		Second three sets, 50 000 kW	
1	Steam pressure at turbine stop-valve, lb./sq. in. (gauge) ..	350		350	
2	Total steam temperature at turbine stop-valve, ° F.	700		730	
3	Absolute pressure at turbine exhaust, lb./sq. in.	0·98		0·98	
4	Heat cycle	Regenerative		Regenerative	
5	Load at economic rating, kW	24 000		40 000	
6	Steam to turbine, lb./hour..	252 228		400 480	
7	Steam to ejectors, lb./hour	1 380		1 800	
8	Steam to condenser, lb./hour	203 830		328 236	
9	Temperature corresponding to vacuum, ° F.	101		101	
10	Temperature of condensate, ° F.	101		101	
11	Quantity of make-up feed-water at 60° F., lb./hour	12 000		20 024	
12	Bled steam, quantities and pressures:—	Lb./hour at	lb./sq. in.	Lb./hour at	lb./sq. in.
	(*a*) High pressure	13 300	76·8	29 065	83·0
	(*b*) Intermediate pressure	11 750	34·9	22 504	27·0
	(*c*) Low pressure	22 030	15·6	20 675	8·2
13	Condensate temperature (° F.) leaving:—				
	(*a*) Ejector heater	107		106·5	
	(*b*) Drain heater	120·5		No drain heater	
	(*c*) Low-pressure heater..	203·5		176	
	(*d*) Intermediate-pressure heater	248		236·3	
	(*e*) High-pressure heater	295		306	
14	Total B.Th.U. absorbed from steam to produce 1 kWh ..	11 636·8		11 113	
15	*Auxiliary power (as fraction of output):—				
	(*a*) Turbine room	0·0234		0·02955	
				P.F.†	S.F.‡
	(*b*) Boiler house	0·0350		0·0350	0·0204
	(*c*) Coal and ash plant, etc.	0·0090		0·0090	0·0090
	Total of (*a*), (*b*), and (*c*)	0·0674		0·07355	0·05895
16	*Combustion heat efficiency of boiler plant, %	84·5		84·25	79·6
17	Overall efficiency, including auxiliary power at economic rating, %	23·11		23·96	22·99

* With fuel containing 20 % moisture. † Pulverized-fuel firing. ‡ Stoker firing.

Table 12

PARTICULARS OF MAIN TURBO-ALTERNATORS AND CONDENSING PLANT

Item	Description	First three sets (each plant)	Second three sets (each plant)
1	Number of sets	3	3
2	Maximum continuous rated capacity of main alternators	30 000 kW	50 000 kW
3	Economic rating	24 000 kW	40 000 kW
4	Capacity of direct-coupled auxiliary generator, kW	400 (d.c.)	1 500 (a.c.)
5	Speed, r.p.m.	1 500	1 500
6	Critical speed of turbine rotor, r.p.m. (approx.)	1 950	2 740 h.p. 2 000 l.p.
7	Steam pressure at turbine stop-valve, lb./sq. in.	350	350
8	Total steam temperature at turbine stop-valve, ° F.	700	730
9	Type of blading	Impulse	Reaction
10	Total number of stages	37	70
11	Vacuum at maximum continuous rating, in. Hg	28·0	28·0
12	Total steam to condenser at economic rating, lb./hour	203 830	328 236
13	Total condenser surface, sq. ft.	45 000	65 000
14	Temperature of inlet circulating water, ° F.	75	75
15	Temperature of condensate leaving condenser, ° F.	101	101
16	Steam to ejectors, lb./hour	1 380	1 800
17	Number of heater stages (including drain and ejector heater)	5	4
18	Final feed-water temperature with 5 % make-up water, ° F.	295	306
19	Guaranteed heat consumption at economic rating, including auxiliary power, B.Th.U./kWh	11 915·6	11 451·4
20	Capacity of surge tank, lb.	160 000	350 000
21	Capacity of feed-water reserve tanks, lb.	160 000	200 000
22	Feed-pump discharge pressure, lb./sq. in.	512	512
23	Capacity of each feed pump, lb./hour	500 000	520 000
24	Feed-water quantity, including 5 % make-up feed-water, lb./hour	264 290	420 504
25	Motor horse-power, B.S.S. rating:—		
	Each feed pump	440	550
	Each circulating-water pump	400	580
	Each extraction pump	50	90

Table 13

PARTICULARS OF MAIN ALTERNATORS

Item	Description	First 3 alternators	Second 3 alternators
1	Output of main alternator, kVA	37 500	62 500
2	Alternator efficiency at full load and 0·8 p.f., %	97·0	97·7
3	Voltage between phases	11 000	11 000
4	Output of auxiliary generator, kW	400 (d.c.)	1 500 (a.c.)
5	Output of exciter, kW	110	176
6	Critical speed of alternator, r.p.m.	2 100	1 820
7	Air-cooler effective surface, tubes and fins, sq. ft.	17 300	11 180
8	Air inlet temperature, ° F.	128	127
9	Air outlet temperature, ° F.	85	85
10	Air circulated, lb./hour	326 000	450 000
11	Water inlet temperature, ° F.	75	75
12	Water outlet temperature, ° F.	81	84
13	Water circulated, lb./hour	595 000	480 000
14	Alternator internal reactance, %	18	16·6
15	Rotor temperature-rise (deg. F.) at full load, 0·8 p.f.	162	162
16	Stator temperature-rise (deg. F.) at full load, 0·8 p.f.	144	144
17	Inherent regulation:—		
	At 0·8 p.f.	45 %	46 %
	At 1·0 p.f.	26·5 %	29 %

Table 14

PARTICULARS OF MAIN TRANSFORMERS

	Item	12 000 kVA (after rewind to 50 cycles)	15 000 kVA
1	Primary voltage	11 000	11 000
2	Secondary voltage	33 000	33 000
3	Iron loss (normal full load)	25 000 watts	28 000 watts
4	Copper loss (normal full load, unity p.f.)	62 000 watts	115 000 watts
5	Regulation:—		
	At full load, 1·0 p.f.	0·7 %	1·13 %
	At full load, 0·6 p.f.	5·1 %	7·00 %
6	Efficiency at unity power factor:—		
	125 % full load	99·20 %	98·9 %
	100 % full load	99·28 %	99·06 %
	50 % full load	99·31 %	99·25 %
7	Temperature-rise of oil at full load (maximum temperature of ambient air 40° C.)	50 deg. C.	50 deg. C.

Table 15

OPERATING STATISTICS

Item	Description	1935	1936	1937
1	Units sent out	422 347 527	621 534 100	908 826 700
2	Percentage of units generated used on works	6·73	6·81	6·67
3	Maximum load sent out, kW	90 600	158 600	201 000
4	Station yearly load factor, %	53·2	44·6	51·6
5	Engine-room running plant load factor, %	82·6	80·6	82·5
6	Overall thermal efficiency (on units sent out), %	21·78	21·71	21·42
7	Engine-room thermal efficiency, %	26·60	26·65	26·71
8	Boiler-house efficiency, %	81·91	81·20	80·19
9	Average steam temperature at superheater stop-valve, ° F.	735	718	706
10	Average steam pressure at superheater stop-valve, lb./sq. in.	370	370	370
11	Average absolute back pressure at turbine exhaust, lb./sq. in.	0·79	0·78	0·72
12	Average cooling-water inlet temperature, ° F.	63	65	65
13	Average cooling-water outlet temperature, ° F.	81	81	80
14	Average feed-water temperature, ° F.	295	295	294
15	Average flue-gas temperature, ° F.	305	329	347

Table 16

PERFORMANCE OF COAL-HANDLING PLANT

Description	Actual operating conditions	Test results
Coal to bunkers:—		
Average tonnage per hour (average fuel)	77·5	
Maximum tonnage per hour (good fuel)	100	100
Minimum tonnage per hour (wet fuel)	50	
Coal to store:—		
Average tonnage per hour	60	100
Reclamation from store to bunkers:—		
Average tonnage per hour (average fuel)	55	
Maximum tonnage per hour (good fuel)	80	100
Minimum tonnage per hour (wet fuel)	30	

Table 17

PERFORMANCE OF BOILER UNITS

Test Results, Normal Load

		Pulverized-fuel boiler	Stoker-fired boiler
1	Water evaporated, lb./hour	170 998	250 383
2	Temperature of feed to boiler, ° F.	293·7	305·9
3	Temperature of feed leaving economizer, ° F.	—	392·7
4	Steam pressure at superheater outlet, lb./sq. in.	361·3	358·2
5	Pressure-drop through superheater, lb./sq. in.	4·8	24·5
6	Steam temperature at superheater outlet, ° F.	721·8	751·8
7	CO_2 at boiler outlet, %	15·46	12·41
8	Temperature of air entering forced-draught fan, ° F.	89·2	98·8
9	Temperature of air leaving air heater, ° F.	442·2	288·6
10	Temperature of flue gas leaving boiler, ° F.	331·4	304·3
11	Rate of heat liberation in combustion chamber, B.Th.U./cu. ft./hour	15 860	23 937
12	Heat transmission per sq. ft. of generating surface, B.Th.U./hour	7 263	8 150
13	Fuel burnt per sq. ft. of grate area per hour, lb.	—	51·0
14	Fuel (as weighed):—		
	Calorific value (gross), B.Th.U./lb.	10 904	10 451
	Moisture, %	11·30	13·98
	Ash, %	11·32	11·43
	Sizing, % through ⅛-in. mesh	—	48
	Coking index	—	5–10
15	Overall thermal efficiency:—		
	Combustion heat (gross) efficiency, %	86·14	85
	Equivalent of power consumed by auxiliaries and lost by radiation, %	2·92	1·72
	Net overall thermal efficiency, %	83·22	83·28
16	Net overall thermal efficiency corrected to specified conditions, %	84·55	84·33

Table 18

PERFORMANCE OF TURBO-ALTERNATORS

Turbo-Alternator and Condenser Test Results—Economic Rating

		30 000-kW sets	50 000-kW sets
Turbine Test:—			
1	Economic rating. Load on alternator, kW	24 478·7	40 263
2	Steam pressure at turbine stop-valve, lb./sq. in. (gauge)	347·1	346
3	Steam temperature at turbine stop-valve, ° F.	693·4	692·5
4	Vacuum in condenser, in. Hg	27·830	28·105
5	Feed-water temperature, ° F.	296·8	308·6
6	Steam consumption (including ejector steam), lb./kWh	11·135	10·4620
7	Steam consumption corrected to specified conditions, lb./kWh	11·035	10·0854
Condenser Test—Feed Heating:—			
8	Load on alternator, kW	30 850*	40 000
9	Steam to condenser, lb./hour	276 151	353 062
10	Vacuum at exhaust flange, in. Hg	28·660	28·570
11	Vacuum drop between ejector suction and turbine exhaust flange, in. Hg	0·392	0·301
12	Inlet temperature of circulating water, ° F.	57·57	70·40
13	Outlet temperature of circulating water, ° F.	78·77	85·76
14	Quantity of circulating water, gallons per min.	20 356	32 603
15	Pressure-drop of circulating water across condenser, lb./sq. in.	2·87	3·61
16	Temperature of condensate and drains leaving condenser, ° F.	80·9	89·7
17	Temperature corresponding to vacuum, ° F.	85·3	90·06
Alternator Test (Heat Run):—			
18	Stator, kVA	37 530	62 130
19	Stator voltage	11 222	10 946
20	Stator power factor	0·79	0·7993
21	Rotor current, amperes	451·7	743·4
22	Stator maximum temperature-rise in slots (by thermocouple), ° C.	51·4	62·4
23	Stator end-winding temperature-rise (by thermocouple), deg. C.	39·4	38·1
24	Stator iron temperature-rise (by thermocouple), deg. C.	30·1	48·8
25	Rotor temperature-rise (by resistance method), deg. C.	87·6	82·7
26	Air inlet temperature to alternator, ° C.	23·1	28·8
27	Air outlet temperature to alternator, ° C.	43·5	56·0
28	Air quantity, lb./hour	346 000	367 500
29	Internal reactance, %	22·7	20·9
30	Inherent regulation, %	50	40·4

* No test carried out at economic rating.

Table 19

COOLING TOWERS—TEST RESULTS

Circulating water to tower	2 736 900 gallons per hour
Mean temperature of water to tower	91·4° F.
Mean temperature of water from tower	77·66° F.
Wet-bulb temperature	59·6° F.
Dry-bulb temperature	65·1° F.
Calculated humidity	72·2 %

[The discussion on this paper will be found on page 498.]

DISCUSSION BEFORE THE INSTITUTION, 9TH MARCH, 1939

Mr. A. Pollitt: The Hams Hall station was designed in 1926, and I take it that the steam conditions would be modified were the station being designed to-day.

The thermal efficiency of such a station depends chiefly on the load factor and the general station load rather than on such characteristics as the price of coal.

The author's reference to the ash- and grit-handling plant reminds me that I noticed on my last trip to the United States that some of the undertakings there were beginning to use grit from pulverized-fuel boilers as an aggregate for paving and partition slabs.

It would be interesting to know whether the author has made any tests to determine how the performance of the cooling towers varies with climatic conditions.

He tilts slightly at those who believe in steam-driven auxiliaries, and does not make it clear whether he has any steam-driven emergency boiler feed pumps on his system. I still like to have a turbo-driven boiler feed pump or two for emergency work.

The feed-water treatment figures of the undertaking with which I am associated are somewhat different from those given in the paper. In normal conditions the conductivity of the author's untreated condensate varies from about 4 to 8 degrees, while the best figures that we get vary from 0·4 to 1·0 degree. Whereas at Hams Hall the undissolved solids amount to 40 to 60 grains per gallon, our figure is never above 20, and is more usually about 10. Our figure for oxygen content is 0·01 millilitre per litre, measured at the feed pumps. This is outside the range of the Winkler apparatus, and our chemists have devised special apparatus to give an exact reading for this low figure.

Referring to the load curves shown in Figs. 12 and 13, it is rather remarkable that the summer curve and the winter curve for 1935 are almost identical except for a short peak between 16 and 18 hours. I should be interested to know the reason for this unusual feature.

I do not see how the Willans line given in Fig. 15 can be correct if it passes through zero at no load. My own experience in regard to power-station performance curves has shown that so many variable factors are involved that it is not possible to draw a curve through zero, although theoretically such curves are possible. I should be interested to know how the theoretical figures shown in Fig. 16 were calculated and how the actual curve was deduced.

Table 11 shows figures for combustion heat efficiency of 84·25 % with pulverized-fuel firing and 79·6 % with stoker firing. I should be interested to see the comparative heat figures showing how the difference of 4·65 % is made up.

On page 473 the author refers to a factor which limits the use of preheated air on stokers. I suppose that that limitation applied when the station was designed, but perhaps the author will agree that to-day the temperatures of preheated air employed with stokers, and especially retort-type stokers, are as high as 450° F.

Mr. C. L. Blackburn: The Hams Hall station was perhaps the first cooling-tower station in this country designed on a large scale and for high efficiency. At the time when it was first projected, cooling-tower stations were generally regarded as destined to be supplanted by stations erected on riverside sites, which could get all the cooling water they wanted without the necessity for evaporation. As time has gone on, the number of adequate riverside sites has become more and more restricted, and such as remain are apt to be increasingly expensive to develop. The cooling-tower station is to-day creeping up as a rival to the riverside-site station, and will no doubt continue to gain upon it.

I am interested in the reference to the amount of cooling-water make-up used, showing that the amount of water taken in is twice the amount evaporated, so that the amount of water rejected to wash away the silt is approximately equal to the amount evaporated. Under those conditions it works out that the average concentration of silt in the circulating-water system will be approximately twice that in the make-up water. The relation is that if one throws away n times as much water as one evaporates, the concentration of soluble and suspended matter in the system is $\left(1 + \frac{1}{n}\right)$ times the concentration in the make-up. It seems a convenient working rule to throw away at least an equal amount to that which is evaporated, and thereby keep the concentration not more than double that of the make-up water.

Regarding the question of cooling-tower performance, the author's figures for the increased cost for a given improvement in vacuum seem surprisingly high. Can one arrive at a representative performance figure by taking average climatic conditions? The question is whether some weighting of the summer and winter figures is necessary, and whether in comparison with figures based on average conditions one may lose more in the summer than one gains in the winter, or vice versa.

Apparently the fluid used for condensing purposes at this station is particularly corrosive. The pump impellers are of gun-metal, and it would be interesting to know whether the casings of the pumps are also of gun-metal.

It appears from Fig. 8 that the unit generators used for auxiliary supplies are only of 1 500 kW, and therefore only a limited number of the auxiliaries can be connected to them. If it is claimed that it is necessary from the point of view of reliability to employ auxiliary generators to safeguard the auxiliary supplies, it seems important that one should connect to them all those auxiliaries which are essential to maintain the generating plant in service. As a compromise, the unit transformer has a considerable number of the advantages of a unit generator, with less cost, but where it is employed it is the usual practice to connect all the essential auxiliaries to it and to give it a capacity approximately 3 times that of the auxiliary alternators shown in Fig. 8.

On page 471 the author refers to the buildings as having been constructed in accordance with the L.C.C. Regulations. This seems a little surprising in view of the fact that the buildings are not in the L.C.C. area, and that the Regulations are generally regarded as expensive to comply with. An interesting point about the new Hams Hall station is that the buildings are constructed of ferro-concrete, which appears to have a growing advantage in

comparison with steel-frame construction now that buildings have to be made solid enough to stand up to blast and splinters from enemy bombs. By approximately what period was the progress of the erection work delayed in consequence of the adoption of ferro-concrete buildings? In a steel-frame building it is possible to get the turbine-house crane-ways up and the crane working before work is started on the foundation blocks, but with ferro-concrete a considerable time must elapse before one can get a crane working to handle the heavy items of plant and put them into position.

One broad question of design which is raised in the paper and on which I do not see eye to eye with the author is that of the load factor to be assumed when considering new developments. He would say that every station must, over its whole life, work on a lower average load-factor than that obtaining when it is first put into service, and that therefore we should not incur capital expenditure that cannot be justified by increased efficiency on a 40 % load-factor basis. By following this argument too closely one arrives at the position that all new plant should be equally efficient and the load might just as well be equally spread, with no distinction between base-load and peak-load plants. There has in the past been a tendency for the load factor of any particular plant to diminish with time, but that tendency is likely to be less marked in the immediate future, because there will clearly not be the scope for progress in the way of making base-load plants more efficient that there has been in the past. In fact, there is probably now more scope for making some of the intermediate-load-factor stations and peak-load stations cheaper. We should therefore assign a definite base load to certain stations and calculate their optimum design on the assumption of perhaps 70 % load factor, that of others on a 40 % load factor, and so on, down to load factors of 10 % and lower for peak-load stations.

If stations specially designed for lower load-factors continue to operate on those load factors, the load factor on the base-load plants will be maintained and will not fall as time goes on. It is surely more economical to have a variety of designs each adapted to its own load factor than to have a common design and a common load factor for all.

Mr. C. W. Priest: One of the first things that strikes me about the Hams Hall station is the large area occupied by the site and its comparatively low cost, namely £23 an acre. I should like the author to indicate how much of this site will be fully occupied when the second Hams Hall station is complete. Even after allowing 300 acres for the ash dump, with the 700 acres remaining the total capacity per acre will be only about 800 kW as compared with the 35 000 kW to 40 000 kW per acre in the case of some London stations. In London a station of the same installed capacity as Hams Hall occupies 12 to 15 acres, costing up to £40 000 per acre.

I should like to know whether the figure of capital cost for the existing Hams Hall station given in Table 7 includes the capital charges incurred while the station was under construction, and, if possible, the extent of those charges.

In several recent large stations the question of transmission costs has loomed so large in the total economy that the designers have had to close their eyes to the possibility of building a station on a site of comparatively low value, and have had to come into the crowded areas where sites are very expensive. Hams Hall is 9 miles from the centre of Birmingham, which is fed by 19 trunk feeders at 33 kV. Presumably the majority of the output has to be transmitted the whole distance. Perhaps the author will state the charge per kilowatt, and the running charge, due to the transmission system.

It is rather surprising to find a station of this size and with these conditions relying on the lime Zeolite treatment with a make-up water of 1 grain per gallon hardness. To some extent this is explained by the fact that the boiler blow-down figure averages about $1\frac{1}{4}$ % of the total evaporated. With a station using evaporated feed-water it is possible to cut the boiler blow-down down to about 0·25 %, so that the remaining 1 % might be debited against the cost of water treatment given in Table 5. If my inferences and assumptions are correct, the addition of the cost of that 1 % will about double the cost of the water treatment given in Table 5.

Mr. W. E. Burnand: When I was apprenticed in 1892 to the Sheffield Telephone Exchange and Electric Light Co., the generating plant took up a large proportion and the accessories only a minor proportion of the room available. Table 1 shows that at Hams Hall the areas taken up by the switchgear and the turbines are 35 000 sq. ft. and 56 000 sq. ft. respectively.

I have never been in favour of the oil switch, since it introduces a severe fire hazard and a medium not adapted to absorbing a quick power surge, and also concentrates the arc so that it will do the maximum of damage to the contacts. I remember that the old Raworth switch, where the break was under water, was quite satisfactory; surely it could have been developed into a more scientific apparatus than the oil-break switch. Water is an excellent medium for absorbing and dispersing energy, and coupled with means for de-ionizing gases it could deal with large amounts of power without fuss. Other possibilities are the use of alloys which give off a non-conducting vapour, and a development on the lines of the mercury rectifier, which breaks circuit millions of times in a day without damage. An oil circuit-breaker cannot make 1 000 breaks in its lifetime without destruction.

A striking point which emerges from the paper is the rise in the cost of coal. Table 7 shows the cost of switchgear and main transformers to be £117 000 and £129 000 respectively. There is no sense of proportion about such figures. The transformers are at work all the time, whereas the switch operates during a small fraction of a millionth of its life.

The efficiency of the dust-extraction plant at Hams Hall is shown by the fact that the hedges and the grass round about bear no sign of dust.

Mr. W. N. C. Clinch: No mention is made in the paper of the facilities for testing the Hams Hall plant. The commercial means of testing is probably based on a week's or a month's run. It would be interesting to know what the recognized figures of operation are.

One of the author's slides showed the make-up water as being evaporated by bled steam. This practice has one disadvantage, unless, of course, the author is assured that

the load factor of the station will always be as good as is indicated on the charts. This is that, as the load falls, the bled-steam temperature decreases, and a state of affairs occurs where it is impossible to obtain make-up.

Turning to page 478, I should be interested to learn what the biological deposits were on the condenser tubes, and in what manner they were removed. So far as the feed-water treatment is concerned, I am surprised to learn that it is possible to handle feed-water such as is indicated in the first section of Part 2. The method of operation is evidently that made possible by blowing-down the boilers frequently, but at the same time lowering again, by a certain percentage, the thermal efficiency of the station.

I suggest that the Willans lines shown in Figs. 15 and 16 should be ascribed to Mr. R. H. Parsons. The Parsons line shows more accurately the complete performance, not of a generating section but as a power station, including the boilers and other auxiliary plant.

I cannot follow the author's reason for condemning steam-driven auxiliaries so far as boiler plant is concerned. Most of us have experienced trouble in a power station and been glad to make use of a steam feed-pump. Unless it is proposed to utilize in the new station for works power purposes some of the plant in the older section, it is necessary to have available a stand-by source which can continue to supply the essential auxiliaries, without being affected by frequency variations which may occur during a period of overload caused by any emergency existing anywhere on the system.

Turning to the question of air heating, it is an established fact that with retort stokers and pulverized-fuel boilers it is possible with advantage to increase the air temperature, but with chain-grate stokers one is somewhat restricted as regards temperature, and for the purpose of economy it is necessary to maintain a lower air temperature.

I should be pleased to learn whether the heat efficiency figures in Table 11 represent the net or the gross boiler efficiency.

In his " Conclusions " the author says " To-day it is orthodox to worship at the shrine of financial economy and to abandon the altruistic and heroic cult of thermal efficiency, yet should coal conservation become essential these ideals would be sharply reversed." If the author will reconsider that paragraph I suggest that he will find his views without general support. The progress in the design of power-station plant does in itself bring about a conservation of fuel, and to attain this end consideration must be given to the cost which the electricity consumer can bear.

Mr. J. R. Finniecome (*communicated*): One of the most remarkable developments in recent years has been that of the cooling towers for large power stations. Timber was originally used for the construction of these towers, but it is being superseded by reinforced concrete, and the customary prismoidal type of tower is now giving place to the hyperboloid. The hyperbolic ferro-concrete cooling tower owes its success to the fact that it (1) has a very low maintenance cost, (2) is fireproof, (3) is suitable for resisting severe storms, (4) has a large cooling surface per square foot of area, (5) permits higher coolers, (6) can be designed with safety for any reasonable height, (7) has greater strength of structure than other types of tower, (8) can be built in very large units, and (9) has a shape which automatically directs the air stream entering the tower towards the centre and thus creates an excellent draught.

The first tower of this type was constructed in 1917 by Prof. Van Iterson, in collaboration with the chief engineer of the City of Amsterdam. Similar towers were afterwards erected in other parts of Holland, and the first to be installed in this country were erected in 1925 at the Lister Drive power station of the Liverpool Corporation. The ferro-concrete hyperbolic cooling towers at the Hams Hall station are designed for 2 666 000 gallons per hour, i.e. 5·68 times the cooling capacity of the towers at Lister Drive. The height of the Hams Hall towers is nearly double that of the towers at Lister Drive, and their maximum cooling capacity per square foot of area is 1·8 times as great. Other particulars of ferro-concrete cooling towers in operation in this country are given in Table A.

The author's fuel, generating, and total working costs compare well with those of other large supply undertakings. Generally the fuel cost represents 70 % to 80 % of the generating cost, but at Hams Hall the value for 1937 was 82·5 %. The fuel cost is usually 50 % to 60 % of the total working cost, and was 56 % at Hams Hall for 1937.

[Mr. Finniecome's contribution was accompanied by two charts giving (*a*) the fuel cost as a function of coal consumption and price of coal; (*b*) the cost of fuel per kW of maximum generator load, in terms of the load factor and the price of coal.]

Mr. A. W. C. Hirst (*communicated*): Reference was made during the discussion to the question of oil-less switchgear, and it is interesting to note that such gear, of the air-blast type, is long past the experimental stage on the Continent. One Swiss firm alone has already in operation some 2 000 units for voltages up to 220 kV and rupturing capacities up to 4 000 MVA, including over 70 in operation in this country on systems of 3·3, 6·6, and 33 kV, with rupturing capacities up to 750 MVA. This type of gear undoubtedly has an assured future, quite apart from its immediate particular interest from the point of view of air raid precautions.

Mr. L. M. Jockel (*communicated*): In regard to Part I of the paper, I am surprised that the superstructure is designed to the L.C.C. Regulations, which, at the time of the original design—some 12 years ago—were considered to be most conservative and unnecessarily expensive in their adoption. Doubtless there was some good reason for their application at the Hams Hall station.

I notice that coal is delivered to the station in 10- to 12-ton trucks and I believe the Birmingham Electricity Department owns an appreciable number of wagons; but I should have thought that 20-ton vehicles would have been a more profitable proposition.

Regarding sidings accommodation, 1½ days' capacity for loaded wagons seems unduly small. A design figure of 3 days' capacity would be more normal, and worth the extra capital expenditure entailed.

When dealing with the class of coal utilized, the author gives data based on the " as received " or " as fired " calorific value (incidentally, the figures should be rounded

Table A

SOME FERRO-CONCRETE HYPERBOLIC COOLING TOWERS FOR LARGE POWER STATIONS IN ENGLAND

Year installed	1925–27	1928	1926–29	1929–30
Owner	Liverpool Corporation	Coventry Corporation	Leicester Corporation	Birmingham Corporation
Power station	Lister Drive No. 3	Longford	Freeman's Meadows	Hams Hall
Number of towers	5	4	5	6
Total normal cooling capacity, gall. per hour	3 000 000	3 200 000	4 125 000	19 200 000
Total maximum cooling capacity, gall. per hour	4 750 000	4 800 000	6 150 000	28 800 000
Normal cooling capacity of each tower, gall. per hour	600 000	800 000	825 000	3 200 000
Maximum cooling capacity of each tower, gall. per hour	950 000	1 200 000	1 230 000	4 800 000
Quantity of water to be cooled per tower, gall. per hour	470 000	528 000	697 500	2 666 000
Temperature of water entering tower, ° F.	102·5	92·0	84·0	92·0
Temperature of water leaving tower, ° F.	83·0	75·0	72·0	75·0
Difference in temperature before and after cooling, ° F.	19·5	17·0	12·0	17·0
Atmospheric wet-bulb temperature, ° F.	55·0	55·0	52·0	52·0
Total height, ft.	118·0	130·0	128·0	210·0
Diameter at base, ft.	100·0	100·0	99·0	168·0
Diameter at throat, ft.	42·0	51·0	53·0	86·0
Diameter at top, ft.	49·0	58·0	60·0	92·4
Area at base, sq. ft.	7 854·0	7 854·0	7 700·0	22 168·0
Maximum cooling capacity per sq. ft., gall. per hour	121·0	153·0	160·0	217·0
Ratio: (Total height)/(Diameter at base)	1·18	1·30	1·29	1·25
Ratio: (Diameter at throat)/(Diameter at base)	0·42	0·51	0·535	0·512
Ratio: (Diameter at top)/(Diameter at base)	0·49	0·58	0·606	0·55

off) and then quotes later the net calorific value, which is rather confusing. All values should be on a similar basis for comparison, i.e. the gross calorific value, either "as dried" or "as fired."

When purchasing fuels on an order-of-merit basis, it is frequently desirable to include amongst the other data the average annual cost of refractory maintenance of the boilers, particularly when low-grade coals are used.

In regard to the auxiliary power circuits, a great deal could be said as to the various systems available, but the concensus of opinion to-day is undoubtedly in favour of a.c. squirrel-cage motors operating at 400 volts, and in the case of machines of, say, 100 b.h.p. and upwards, a pressure of either 3·3 or 6·6 kV. The author's opinion as to the economics of 400-volt versus 3 300-volt auxiliary motors is most valuable, and he is doubtless aware of the difficulties that may obtain with heavy 400-volt cables, particularly in the boiler houses.

It would be of value if he could throw some light on the effect of external interruptions or surges on the auxiliary supplies at Hams Hall, such as occurred about 3 months ago. Complete stability is hardly to be expected owing to the magnitude of such external faults, and the designer cannot guard against all emergencies

and yet maintain reasonable simplicity in layout together with a moderate capital cost.

On page 482 the importance of feed-water treatment is mentioned, and in regard to concentration in the boiler the figure of 40 to 60 grains per gallon seems unduly low for the steam pressure carried. It should be quite possible to operate confidently at 100 to 120 grains per gallon of dissolved solids with little blowing-down except under condenser-leakage conditions. Sodium-phosphate conditioning is probably used when starting away the boilers, and in order to maintain correct treatment during long steaming periods an injection system is useful.

I have designed and successfully used an injection pump for maintaining the necessary chemical balance in the boilers, and satisfactory control can thus be obtained even where there is organic matter in the circulating water. The use of evaporators, however, seems to be indicated in the existing station, apart from their adoption in the new " B " station.

Finally, on page 491 it is stated that for the steam pipes in the new station, plain instead of corrugated expansion bends will be used; I should like to ask the author whether this decision is due to either the pressure-drop or the " whistling " phenomena of such pipes, or to the economics of flexibility as compared with the increased capital cost.

Mr. G. L. E. Metz (*communicated*): The author's figures of capital cost per kilowatt of plant installed (Table 7) compare favourably with the capital costs of modern base-load stations in this country, which have been given recently as £14 to £17 per kilowatt installed. His decision to employ 50 000-kW sets and a higher steam temperature and pressure is in accordance with what has become almost standard practice for modern base-load stations.

It would be helpful if the author could explain in greater detail why he favours direct-wound 33-kV machines, as this preference appears to be hard to justify when low-price fuel is obtainable. The capital and fuel savings obtainable from 33-kV turbo-alternators cannot be very great, and while reliability of a 33-kV direct-wound machine is not questioned, it can hardly equal that of an 11-kV alternator and step-up transformer where the higher-voltage winding is under oil and risks of ionization troubles are accordingly eliminated.

I should welcome a few more details regarding the type of switchgear the author proposes to use in the new station. In this country most modern stations of the size of Hams Hall are equipped with metalclad switchgear, a type of equipment which has never been popular for large power stations on the Continent. It would be interesting if the author could say whether he proposes to use cellular or metalclad switchgear of the conventional type, or whether he favours the more recent types where the oil quantity is reduced to a very small value, or no oil at all is used for arc-quenching.

[The author's reply to this discussion will be found on page 509.]

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 6TH MARCH, 1939

Mr. F. Forrest: Birmingham unfortunately does not stand on the banks of a large river, and the Hams Hall site was chosen because it is adjacent to the main outfall from the sewage works, the purified effluent from which is used for condensing water. A close investigation made a few years ago showed conclusively that even with the lower thermal efficiency due to the use of cooling towers, the cost of the unit delivered to the consumer's terminals from Hams Hall station was lower than would have been the case if we had gone some 14 miles farther afield to obtain a riverside site.

Hams Hall " A " station, which the author describes, contains 240 000 kW of generating plant, and the new station, Hams Hall " B," which is being erected about 800 yd. from the existing station, will ultimately have 300 000 kW of plant installed. The two stations will have siding connections to the L.M.S. main Birmingham–Derby lines, and in laying out the siding accommodation common to the two stations we have had to face the possibility of a maximum ultimate coal consumption of some 8 000 tons per day. This I am satisfied is the greatest quantity that the railway can handle at this site. This question of providing fuel supplies by rail must in future have a very great bearing upon the location and plant capacity of large power stations.

When originally designed Hams Hall station was considered to be in the heart of the country, but the movement of industries from the centre of Birmingham is rapidly changing the character of the countryside. In the course of a few years the station will probably be surrounded by factories and the homes of the employees, who will be working and living under very much better conditions than prevail to-day. This in turn will have the effect of shortening the average length of the transmission cables and reducing the capital cost and losses associated with them.

The arrangement of the boilers and turbines at Hams Hall has enabled us to keep the steam pipes short. We have arranged most of the operating floors on one level, so as to reduce labour; we have endeavoured to keep oxygen out of the feed water, and by electrostatic precipitators (which have an efficiency of some 95 %) have practically eliminated grit and dust from the flue gases discharged to atmosphere.

In the " A " station we have separated the e.h.t. switchgear by fireproof partitions, and we are going one step farther in the case of the " B " station, where we shall put up not one switch-house but six separate switch-houses—one for each alternator with its complement of feeders.

There is one question in connection with these big power stations which is giving some of us food for thought, and that is the best method of connecting the grid to the busbars. If, as is mostly the case at present, there is a common busbar to which all the generators and the grid are connected, and if something unforeseen happens to those busbars, the grid cannot act as a stand-by to the machines, or vice versa. It seems to me that the present arrangement might with advantage be modified and three busbars provided—one to which the

generators would be connected, one to which the grid would be connected, and a third to which all the outgoing feeder cables would be connected, and which in turn would be connected to the machine busbar and also to the grid busbar. This arrangement would of course have to be modified to suit special conditions where existing feeder busbars are divided into sections.

The total number of men employed at Hams Hall is 228, or one man for every 1 050 kW of plant installed.

We have endeavoured to eliminate dust and dirt from the surroundings of the station, and the extensive lawns and flower beds which have been provided have a further good effect upon the morale of the staff.

Dr. C. C. Garrard: In power-station design, as in all engineering, the two great principles are simplicity and attention to detail, and simplicity in design is the main idea of the Hams Hall station. I have never understood why such great weight is attached by the Commissioners to the question of thermal efficiency. In everything with which we have to deal as engineers it is the cost which counts, and so a power station should be judged by the criterion of what is the total cost of making the current.

I see that there are no house service turbines in the new station, but the auxiliary generators are on the main turbine shafts. How does the station start up after a complete shutdown?

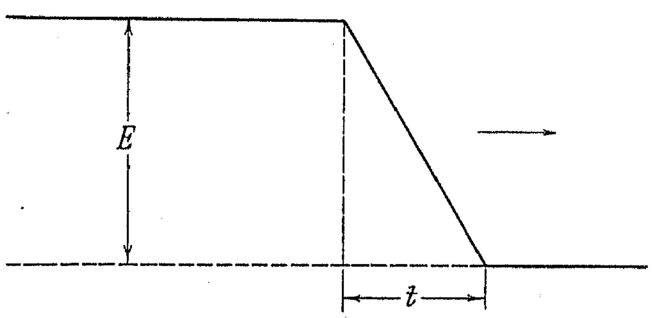

Fig. A

In the new station the Birmingham Corporation has adopted 33 000-volt generators. How do such machines withstand surges? Consider a surge E with a wave-front of time t (Fig. A) approaching an electrical machine. This surge penetrates into the winding with a known velocity of v cm. per sec. (The length of the wave-front will, of course, be altered after it has penetrated.) If we measure along the winding a distance tv centimetres, we reach a point in the winding which we can designate by A. (tv = length of the wave-front inside the winding, in centimetres.) If the terminal point of the winding be called O, then the surge voltage E will exist between the points O and A. It is therefore desirable that these points should be as far away from each other as possible. (Strictly, only those component frequencies of the surge which are below the critical frequency of the winding penetrate; this, however, does not affect the relevancy of the argument.)

Consider now a 4-pole winding of the type having concentric slot conductors consisting of bull, inner, and outer, with 40 slots per phase. If l be the length of half a turn (i.e. core plus one overhang), the length of winding between the bull of the terminal slot and its inner is $3 \times 40 \times l/3 = 40l$. If, on the other hand, we consider a 3-layer lap winding (again with 40 slots per phase), the length of winding between adjacent turns in the terminal slot is $3 \times 40 \times l/60 = 2l$.

Now the wave-front of any dangerous surge (which can penetrate the interior of the winding) is considerably longer than, say, 10 m., which is the approximate turn length of the winding of the large alternator considered. It follows that the surge voltage between turns with the layer-type winding in the case considered, is less than it is with the concentric winding. The ratio between the respective surge stresses varies with the length of the wave-front. For a wave-front of 10 m. (corresponding to 0·067 microsec., i.e. an extremely short wave-front), the surge stresses in the two windings are equal. As the length of the wave-front increases, the relative surge stress in the concentric winding increases, until with a wave-front of 200 m. (or more), corresponding to 1·33 microsec. (or more), the surge stress between adjacent turns in the concentric winding is 20 times what it is in the layer winding. Presumably it is because of this fact that some makers consider that surge protective gear is necessary with 33-kV alternators.

I notice that time-lags of 1·5 sec. are used on the circuit-breakers for the trunk feeders. Is this system being also adopted in the new station? The tendency nowadays is to ask for circuit-breakers to operate in a very short time, with a view to improving stability. It seems to me that if time-lags are artificially introduced by the relays, the object of using these quick-acting circuit-breakers is defeated.

Mr. J. Wilkinson: I should like to ask whether the make-up feed water to the cooling towers of the existing Hams Hall "A" power station is to be obtained in the future from the same source as that to be used for Hams Hall "B," i.e. by drawing on the River Tame water instead of using sewage effluent water.

Dr. M. Kahn: Whilst I agree with the author that there is much to be said for an a.c. house supply, and for the arrangement he has adopted at Hams Hall, namely a house-service alternator direct-coupled to the turbine, it strikes me that this arrangement must necessarily take up a large amount of floor space. This may not matter very much at Hams Hall, where the boiler plant has determined the total length of the power station but it might well be a serious consideration in other power stations where the turbo-alternator sets are arranged crosswise, and not lengthwise as at Hams Hall.

The d.c. system which was adopted in the first section of the Hams Hall station has the advantage that it permits the use of shunt-wound d.c. motors, which allow of easy and economical speed regulation. Speed regulation can be used with advantage on a number of drives in power stations.

What is the author's opinion regarding the use of mercury-arc rectifiers for providing a d.c. supply to this type of motor? It is the particular feature of the mercury rectifier that a short-circuit, or any disturbance on the a.c. system, is not transmitted to the d.c. side. In this respect it has a different characteristic from the transformer, where any disturbance on the high-voltage side is immediately reflected on the low-voltage side, and vice versa. The mercury rectifier can therefore be used in conjunction with a battery for house service supply, either for all the motors or only for the motors which

require speed regulation. Arrangements can be made to connect the transformer of the rectifier alternatively to the busbars of the station or to the supply system, so that either can be used in case the station is disconnected from the supply after a shutdown.

If the battery is allowed to float on the house service supply without giving any current, under ordinary circumstances the full power of the battery will always be available in case of a breakdown for the short time it will be required, until the mercury rectifier can be connected again either to the station supply or to the network. A breakdown on the a.c. supply would cause no disturbance on the house service supply, as the mercury rectifier can be short-circuited on the a.c. side without the d.c. side being affected, and acts at the same time as a valve which will not allow any power to flow through from the battery into the a.c. system.

At large power stations like Hams Hall, it might be preferable to use shunt-wound d.c. motors for all services which require speed variation. I can well imagine that in smaller stations the whole of the auxiliary service may be supplied with direct current, as the total capacity of the battery has only to be made sufficient to last until some a.c. power supply is available, long before the power station is again connected to the supply system. A mercury rectifier with transformer and switchgear can be easily arranged in an annex of the power station. If allowance is made for saving of the valuable space in the power station underneath the crane which is occupied by the house service sets when direct-coupled to the main alternators, I believe that the capital cost of the installation will not be any higher than that of direct-coupled house service alternators. I should be interested to know the author's views on this proposal.

Mr. F. N. Dalman: I should like to know why in Fig. 17 the efficiency falls off along a smooth curve with increasing output.

Mr. C. J. O. Garrard: To-day it is universal practice to control the whole of the electrical side of a power station from a single control room, from which the load and its distribution, the voltage, power factor, frequency, and so on, may be regulated. The boilers, however, are generally under the control of the boiler-room staff, who follow the demand for steam made by the turbines. Nowadays automatic control of boilers has reached quite a high stage of development and is employed in many stations. Would it not be correct to include the control of the boilers in the work of the central control room? One might even regulate the whole power station by adjusting the fuel feed to the demand for power, letting the turbines follow the boilers, instead of vice versa.

There seems to me no doubt that 3·3 kV is the correct voltage for power-station auxiliaries, and even 6·6 kV may come within the bounds of possibility for large stations such as Hams Hall "B." I know of one station in France where 3·3-kV commutator motors were installed to drive the induced- and forced-draught fans, and these, in the time during which I had knowledge of them, worked very well. Their infinitely fine speed regulation was particularly useful in view of the automatic boiler control.

Mr. J. H. Patterson: There are just two points I should like to make with reference to the efficiency of large generating stations.

In the first place, the question of system power-factor seems to me to be of paramount importance. If the amount of reactive current is reduced to an absolute minimum consistent with the safe running of an undertaking, the efficiency of a generating station is bound to be increased. I am aware that the tariffs of most undertakings include a scheme whereby a consumer can obtain a rebate on his bill for a power factor of a certain value, but this, in general, only applies to consumers who take large supplies of electrical energy. I would suggest that some encouragement be given to the smaller concerns taking alternating current from the low-voltage networks, as in many cases the power factor obtaining at these small works is very poor. Some arrangements should be embodied in the scheme whereby condensers or other apparatus are not left switched in during light-load periods.

Secondly, in a large system such as exists in Birmingham, where there are a number of long 33-kV lines and where, during light-load periods, there might be a tendency for a power factor of 0·9 leading to occur, it is not inconceivable that at the end of the lines the voltage might be considerably in excess of that at the generator terminals, on account of the Ferranti effect. In addition, the system might tend to become unstable. I should be glad to know what precautions are taken against such a contingency.

Mr. R. M. Charley: The overall efficiency of the station is of the order of 26 %, whereas the transformer efficiency is about 99 %. It must not be assumed that, because this latter value is so high, any improvement on it may not be justified. Some years ago the contrary was suggested by a power-station engineer. His idea was that a further heat cycle might be added to the system by building a transformer of very cheap materials, in which the losses would be very high, and feeding the heat so generated back into the steam system at a suitable point. I declined then, as I do now, to add a further heat cycle by means of an inefficient transformer!

Seriously, however, I believe that the value of good efficiency in transformers, particularly those intended for distribution purposes, is not given the attention it merits. I realize that the loss saved must be equated to the cost of achieving the saving, but I am satisfied that lower losses than those normally accepted to-day could be justified even at the higher prices that would have to be charged on account of the increased cost of manufacture. I appeal for greater consideration of the question of transformer efficiency with a view to designing for lower losses, both iron and copper.

[The author's reply to this discussion will be found on page 509.]

NORTH-EASTERN CENTRE, AT NEWCASTLE, 13TH MARCH, 1939

Mr. F. C. Winfield: The author and his colleagues are to be commended on the long view which they have taken in regard to site area and the area set aside for ash disposal. It is usually very difficult to secure such excellent provision for these items.

The steelwork for the existing station at Hams Hall is apparently designed to London County Council regulations; I should be glad to know whether there are any local restrictions requiring conformity with these regulations, since in areas outside London sound steel structures can be constructed at a materially lower cost than would normally result from conforming with them.

Whereas from the description of the "A" station it is clear that both electrostatic and cyclone dust and grit precipitators are used, the proposals for the "B" station refer to the former only. I assume that this is explained by the fact that cyclone arresters were already in use when electrostatic precipitators were added, and that electrostatic precipitators do not need the support of cyclone arresters. The author's reference to the method of handling fine ash is interesting. I should have imagined that to attempt to move this in trucks after partial drying to 20 % moisture would have resulted in material solidification, requiring the truck contents to be dug out at the dumping point.

Gunmetal pump impellers and gunmetal-lined steel shafts are employed for the circulating-water system, owing to the corrosive action of the surge effluent. The pump casings are not mentioned: are these of cast iron or of gunmetal?

The cost given for steam and water piping seems unusually low, and I should be glad to know whether this includes all piping on site. Is the fire service equipment, for example, included?

The control room which is projected for the "B" station is to be remote from the turbine room, whereas the control room in the "A" station is arranged to overlook the turbine room. I consider that the electrical operators should be isolated from the turbine room in such a manner that in times of trouble they remain physically detached from disturbances on the steam side, and perform their emergency functions in as calm and detached an atmosphere as possible. I should be interested to know whether this is the point of view which led to the change, or whether the new arrangement is solely due to air raid precautions requirements.

The 200-ampere earthing resistance employed on the 33-kV system would seem to offer very low fault currents for protective purposes. References in the text to earth-leakage protection give some clue to this, but I should like to know whether there are interconnections on the 33-kV system and, if so, how this low-fault-current problem is dealt with in the protective arrangements, both main and stand-by.

I agree that theoretically the unit-generator has some small advantage over the unit-transformer arrangement, but my experience does not indicate that this advantage is an essential and such as to outweigh those of the cheaper unit-transformer scheme with its simpler arrangement and the inherently greater reliability of the unit transformer compared with a shaft-coupled unit generator. In this area and in many other parts of the world we have had nearly 40 years' experience with the unit-transformer arrangement, and our experience has not provided any effective reason for its abandonment. I should be interested to know whether the author's preference for the unit generator is simply the natural expression of a point of view or whether in addition some practical experience in the past has emphasized its advantage.

I note that in the extensions to the "A" station a change-over from d.c. to a.c. auxiliaries was made, and that a.c. auxiliaries are envisaged for the "B" station. In the normal station of to-day, d.c. auxiliaries are not justified, except in one or two minor instances which can be treated specially. The real object of using d.c. auxiliaries is to obtain variable speed control. This is a material advantage only in the case of the boiler fans, and in a.c. practice this requirement can be met reasonably by the use of simple two-speed motors with final damper control. Given this, direct-starting a.c. squirrel-cage motors can be used throughout for essential auxiliaries with one or two minor exclusions, and the more robust and reliable induction motor can be taken advantage of, with, incidentally, a lower cost (both prime cost and maintenance cost).

I should like to make clear that these views do not necessarily apply if a remotely or automatically controlled boiler house, or indeed power station, is under consideration, as certain other features might then control the decision.

Mr. G. H. Martin: In the remarks on pages 475 and 483 concerning the economic heat cycle, reference is made to the "load factor." It would be interesting to know the definition of this load factor. Speaking generally, I think the term "load factor" can be very misleading. In the Electricity Commissioners' Reports the load factor is defined as "the units sent out multiplied by 100 divided by the maximum load multiplied by the hours run." On this basis a 50 000-kW set running at 1/10 load continuously for 1 year would have a load factor of 100 %. The basis is therefore misleading, and useless for comparing performance, because it does not take into consideration the relation between the economic load of the set and the maximum demand. I should be glad to have the author's views on this matter.

Turning to page 480, I agree that the only virtue of steam-driven auxiliaries is the fact that they are not affected by failure in the electric supply; but their disadvantages are legion. Some power-station engineers incorporate a steam-driven pump and specify that (1) provision has to be made in the feed system for condensing the steam, (2) an automatic relief valve is to be provided for discharging to atmosphere, (3) a connection has to be made to discharge direct to the condenser. An arrangement of this kind requires the feed-pump turbine to be provided with glands suitable for remaining tight under conditions of vacuum and pressure. I know of no benefit which in any way compensates for the complication that is occasioned by such an arrangement. A further objection is the possibility of air being drawn

into the feed system through improperly sealed glands on the pump turbine.

I should be glad to learn the author's views on the necessity of maintaining a constant feed pressure in the high-pressure range. Pump units are frequently fitted with hydraulic couplings to enable the pump speed to be adjusted automatically so as to maintain a constant discharge pressure at all loads. I know of stations where an arrangement of this type involving hydraulic couplings is installed, but it has been found more convenient to disconnect the automatic control and manually adjust the speed of the pump when required—otherwise the pump runs on its characteristic. This evidence makes one wonder whether elaborate automatic control gear is really necessary.

The steam conditions at Hams Hall are 350 lb. per sq. in. and 730° F., and it is interesting to note that the necessity for de-aerators has been avoided by the proper operation of the feed system. Even with considerably higher steam pressures and temperatures, if the feed systems are kept in first-class condition and operated correctly there should never be any need to install de-aerators. It is generally known that the feed system at Hams Hall includes a surge control valve. I would say that even this complication could be dispensed with and the feed line connected directly to the surge tank. There are a large number of large power stations running quite satisfactorily without this valve. Unit evaporators are included in the feed system which supply de-aerated make-up for a certain portion of the day in excess of the demand of the boiler, and when the evaporators happen to be shut down a surplus quantity of feed water is allowed to re-circulate from the pump discharge to the surge tank and back to a collecting tank in the basement which is connected to the condenser and controlled by a ball float. Excess water is therefore continually in circulation and the feed pumps rarely have occasion to draw directly from the surge tank. Consequently the feed remains free of oxygen.

The Hams Hall "A" station is equipped with three 30 000-kW and three 51 500-kW turbo-alternators. Each turbine is provided with two or more steam inlets, i.e. groups of nozzles or by-passes. Are six units not sufficiently flexible to enable partial-load nozzles or valves to be dispensed with, thus making the unit as simple as possible? The turbine would then be designed for a maximum and economic rating.

The author mentioned that to increase the vacuum by $\frac{1}{4}$ in. mercury would mean nearly doubling the size of the cooling towers. I think this requires a little qualification. It is very often possible to improve the vacuum without affecting the quantity of water used or its outlet temperature: for instance, where the external head is very large it is economically justified to allow a large friction drop through the condenser and consequently it is possible to provide the latter with two or three passes, so maintaining a high water velocity, which will give an improvement in vacuum.

The first results of the Hams Hall station appeared in the Electricity Commissioners' Report of 1930. The fuel consumption was given as 1·4 lb. per kWh, the efficiency as 22·5 %, and the load factor as 34·6 %. The best results appear to have been obtained in 1934, when the fuel consumption was 1·27 lb. per kWh, the efficiency 23·4 %, and the load factor 55 %. The last Report gives the fuel used as 1·53 lb. per kWh, the efficiency 21·4 %, and the load factor 51·6 %. There is a partial explanation of this apparent fall-away, because in 1936 the basis of computation of the results was changed from "units generated" to "units sent out." This should account for a difference of approximately 7 %, but does not nearly account for the difference when the 9 % reduction in steam used by the 50 000-kW sets shown in Table 18 is taken into consideration.

Mr. F. Dollin: The author's suggestion that there are relatively few general principles common to all power stations may perhaps be questioned. Apart from the present necessity of planning to provide the greatest possible immunity from air raid attack, are not the general principles governing power-station design the same to-day as they always have been, despite the fact that their working-out to obtain the most economic result in practice will produce widely different designs in different circumstances and at different times? How impossible it is for anyone who is not in possession of all the facts to judge of the rightness of a decision is well illustrated by the description on pages 471, 472, and 476 of the conditions which led to the adoption of pulverized-fuel boilers for the first section of the station, stoker-fired boilers for the second, and pulverized fuel for the new "B" station.

It would seem that under present conditions in England it is difficult to show any great financial advantage in adopting a pressure of 1 200 lb. per sq. in., though this pressure is largely used in America and also on the Continent of Europe. The use of a pressure of 1 200 lb. per sq. in. in America has received considerable impetus from the widespread fashion of installing "topping" units, i.e. superposing back-pressure turbines supplied from high-pressure boilers on to existing low-pressure stations. In comparison with complete new condensing installations these topping units do not usually work out as low in first cost as might be expected, but they do enable a large increase of kilowatt capacity to be obtained from an existing and limited supply of cooling water. This advantage can only be realized by adopting a high steam pressure.

As regards reheating, the author states that with coal at 16s. per ton a load factor of 60 % is necessary to justify the extra initial cost of reheating equipment. The thermal gain due to reheating is, of course, a function of the initial steam pressure and temperature, and it would be interesting to know to what steam conditions this conclusion applies and approximately what was the extra capital outlay for reheating equipment.

The author draws attention to the fact that years may elapse between the initiation and the completion of a large station, during which time the economics of the problem will almost certainly change considerably. A logical result of this circumstance is seen in the division of the "B" station into two sections, to facilitate the introduction of more advanced conditions in the second half should this be warranted when the time comes to proceed with it.

One interesting feature of the Hams Hall layout is the disposition of the boilers, which are placed in a single

line. I gather that this arrangement was adopted by the designers with the object of achieving simplicity. It does, however, result in the boilers occupying more length than the generating units, even though the latter are unusually long through having auxiliary generators coupled on to them.

It is good to see that the author gives some prominence to the question of the operating staff. The development of modern high-efficiency plant involves the introduction of more and more auxiliary apparatus and more and more refinement of detail, the advantage of which can easily be lost unless there is a corresponding advance in the standard of operation.

In the advance copies of the paper there is a slight discrepancy* between Tables 11 and 12 in regard to the stop-valve temperature for the second three sets. In passing, it may be worth while to remark that the major part of the difference between the "as run" steam consumption and the corrected steam consumption shown in the second column of Table 18 is due to the test temperature being 37·5 deg. F. below the specified temperature.

It would be interesting if the author would mention more fully what problems have been encountered in the use of sewage effluent for circulating-water make-up. The paper says that cast iron and not mild steel has to be employed for the pipes, but cast iron is by no means immune from corrosive influences and the effluent might be expected to contain traces of impurities (such as ammonia) which would affect non-ferrous materials used for pump sleeves, condenser tubes, etc.

Mr. J. R. Kennedy: I should like to ask the author a few questions with regard to the electrical equipment.

As regards fire-fighting equipment (page 474), does he consider that "Fire-foam" extinguishers are sufficient, and for the future installation will he install fixed fittings for either foam or inert-gas protection? Has he ever had a fire or test discharge dealt with by foam? If so, has any difficulty resulted, due to failure of insulation?

If the station were being planned to-day, would the same size of panel be chosen for the control room, and would marine-type signalling equipment be installed? Is not a telephone system quite good enough for a modern set?

As regards the supply to the auxiliaries, is it not much better to employ higher voltages with direct switching for the larger motors, and step-down transformers for groups of smaller motors?

I am pleased to note from the Conclusions that high-voltage switching is to be adopted in the new station, but why wait for 33-kV generation before doing this? Contemporary stations have generator step-up transformers with 33-kV switching. Further, does the author consider 33 kV a sufficiently high switching voltage for a new station of this size? Has he considered 66-kV or even 132-kV switching?

I am sorry that the author does not give complete and separate electrical costs, including figures for 440-volt switchgear and motor starting equipment. Had 33-kV switching been employed originally it appears that the cost of generator step-up transformers would have been about £0·25 per kW and both switchgear and cabling costs would have been reduced, giving an estimated overall saving of £0·3 to £0·35 per kW compared with the figures shown in Table 7.

* Corrected for the *Journal*.

Mr. J. C. Mitchell: Dealing with the section of the paper headed "Heat Cycle," I would point out that if one station of a group is designed for more favourable external conditions than the others, then that station may be expected to have a higher lifetime load-factor than the others. Since the load factor of the group corresponds to the system load-factor, then the favourably placed station will have a lifetime load-factor better than the system load-factor. Also, as we approach the limit of efficiency permitted by the working fluid, the rate of technical advance is reduced and each successive station has a lengthened period of modernity.

The Birmingham system load-factor in 1926 was 30 %, and in view of the special intention that Hams Hall was to burn coal at a favourable price it seems that a case could have been made for designing the station upon the assumption of a load factor of 40 %. On page 483 the author gives some indication of sharing this view, yet he insists that 30 % was the correct figure for design purposes. The references to the Carville and Dunston "A" stations seem irrelevant, because the rate of obsolescence is now much reduced.

Presumably the soft town boiler feed-water used contains carbonates, which will be converted into sodium bicarbonate after passing through the Zeolite softener. Such water, in addition to being corrosive to pipes and tanks, would produce an acid steam and cause a concentration of caustic soda in the boiler drum. Has any corrosion due to acid steam been found, and are any steps taken to prevent inter-crystalline cracking in the boiler drums?

It is stated in the paper that the feed water is conditioned by the addition of soda ash to the condensate discharge. Seeing that the steam pressure is 350 lb. per sq. in. one would expect rather a heavy accumulation of caustic soda in the boilers for the reason stated above. In Table 5 it is stated that phosphate is added to the drums of each new boiler and also when a boiler is completely emptied. Is the phosphate not added continuously? It would be preferable to soda ash.

The author states that to prevent scale, corrosion, and priming, the concentration of dissolved solids is maintained as low as possible. There is only one way to prevent scale and corrosion and that is by correct conditioning of feed water irrespective of boiler-water concentration. He also states that boiler design is an important factor in preventing scale in boiler tubes. There can be little doubt that boiler design is of great importance so far as it affects the quality of steam and also in preventing the settlement of sludge, etc., in undesirable parts of the heating surface; but boiler design has no influence whatever on the prevention of scale. Unless the feed water supplied to any type of externally heated boiler is correctly conditioned, scale formation is bound to occur, provided, of course, that certain calcium and magnesium salts are present in the feed. The author has, however, raised an important point which boiler designers could note with profit.

It is stated that the oxygen content in the feed water does not exceed 0·1 cm^3 per litre, whilst the oxygen content of the condensate does not exceed 0·03 to 0·05 cm^3

per litre. These are high figures, even for 350-lb. per sq. in. boilers, particularly where steam-air ejectors are used. Such figures suggest that there is air leakage at glands, etc., on the condenser side of the extractor pumps.

It is noted that a continuous system of boiler blow-down is under consideration. Our experience with this system on 150-lb. per sq. in. boilers was fairly satisfactory. It suffers from the rather serious disadvantage of an unavoidable deposition of solids on the walls of the blow-down pipe-line.

To engineers running riverside stations, a station using large cooling towers presents several interesting features, particularly as a great advance in the design of cooling towers has taken place during the last 10 years. Designers of cooling towers are now prepared to cool circulating water down to the average summer temperature of our rivers, so that no longer is it necessary, from this point of view, to build a station on the banks of a large river. At Hams Hall the make-up water is pumped into the suction culvert where it will mix with so much cooled water and then pass through the condensers. Now it is stated farther on in the paper that this water is highly corrosive, though no information is given as to what it contains to make it so. Assuming for the moment that, like many sewage effluents, it contains large amounts of sulphides and ammonia, it would have been better to have passed it through the towers first so as to oxidize part of the constituents before allowing it to pass through the circulating-water pumps and condensers, in which corrosion occurs. It is appreciated that with this scheme the make-up pumps would have to work against a higher head and that more auxiliary units would be used, but it would have the advantage of making the circulating waters less corrosive. This suggestion is made because at Hams Hall trouble is experienced with condenser leakage, which is presumably caused by corrosive circulating water. In this connection our experience has been that where cooling towers are in use very little trouble is experienced from leaky condenser tubes until the tubes have lost, after many years, most of their zinc by dezincification. It is known that ammonia can give rise to inter-crystalline cracking of copper alloys. Has the author experienced failure of the Admiralty-mixture tubes and gunmetal pump impellers?

The author's statement concerning the consequences of leakage in cooling-tower stations being worse than in low-head riverside stations requires, I think, some qualification. In the paper no analysis is given of the sewage effluent or of its concentration in the cooling ponds, but the consequences of leakages in high-head cooling-tower stations can hardly be as severe as those of leakages in low-head stations situated on a tidal river, where the water leaking into the feed water may contain from 1 500–2 000 grains per gallon of dissolved solids.

Many of us would like to know whether these leakages are due to leaky tubes, to packing failures, or to the expanded ends of the tubes. Also, how often do such leakages occur? If the trouble is chiefly due to corrosion of the Admiralty-mixture tubes, it would be interesting to know whether tubes made of another alloy have been tried, and, if so, with what results.

The subject of condenser-tube corrosion is a large and interesting one, and there are many other questions which could be asked, such as the type of corrosion, at what part of the tube does it occur, are the tube ends ever eroded, what is the speed of the water through the tubes, and does the water by chance contain any gritty matter? Replies to all these questions would be useful as they concern points affecting, to some extent at least, the design of the plant.

It is stated that as much water is continuously drained from the towers as is evaporated by the cooling process, and I am curious to know whether this is the only provision made to prevent scale formation in the condenser. At certain stations in this district we find such a provision ineffective, and we have to treat the water in such a way that precipitation of dissolved solids on the condenser tubes is inhibited.

I note that hot air has been re-circulated to reduce corrosion of the plate-type air heaters at Hams Hall. Any further information which the author is able to give on this matter would be most welcome. It appears from the report of the shutdown in November, 1938, that the cyclone grit arresters do not provide adequate protection against the emission of grit from stoker-fired boilers. This is most surprising, as we have not experienced similar trouble in this district. Can I infer from the evidence that at Hams Hall the electrostatic precipitators are adequate for the pulverized-fuel boilers but that the cyclones are inadequate for the stoker-fired boilers?

It would be interesting to know whether the d.c. auxiliary busbars are energized normally by the auxiliary turbo sets or by the motor-generators, and also whether the latter are of the synchronous or the induction type. It seems to me that the d.c. auxiliaries are a weak link owing to the danger of flashover, unless they are well isolated from system disturbances. There is one point which is not quite clear regarding the a.c. supplies. It is stated that the 1 500-kW a.c. generators operate at 3 000 volts and supply all motors above 90 h.p. at this voltage; yet Fig. 8 shows these generators and all motors —great and small—connected to the same 440-volt system.

Apart from these two queries, the layout of the auxiliary supplies is fairly clear, and it appears that whereas the boiler-house auxiliaries would be electrically connected to an external fault, the major turbine-house auxiliaries would be connected to the fault mechanically and would never receive a shock of the same order. One wonders what considerations led the designer to provide a first-class system of unit generators and then to throw away his advantage by supplying the boiler auxiliaries from works transformers. I would hazard a guess that, during the trouble experienced at Hams Hall last November, it was the boiler-house auxiliaries which failed.

Referring to personnel, the author states that the highest standard of skill is necessary and that the ideal is to have each man in his vocation. In this district we select a man on the basis of his apparent aptitude and try him out for a short period of holiday relief, his eventual selection or rejection depending upon the result. As promotion in the manual grades is extremely difficult to provide, it would seem that the presence of a large

number of certificated men with equal paper claims for a particular vacancy would considerably complicate the administration of the station.

The question of total works cost (excluding depreciation) is complicated by the fact that the price of coal is now very different from that visualized in 1926; but the figures given on page 490 show that with coal at 9s. 6·75d. per ton the total works cost in 1937 would have been 0·1079d. per unit sent out, which, whilst a good average figure, is no better than that given by smaller stations burning coal bought for 13s. per ton.

Mr. G. R. Peterson: I should like to ask the author for a little more information about the Willans lines shown in Figs. 15 and 16 and the derived operating-efficiency curve shown in Fig. 17. I take it that the points shown in Fig. 15 give the relation each month between the total thermal value of the coal consumed and the output of electricity. While admittedly, as the author points out, the Willans line as drawn is not strictly accurate, in that the monthly fixed heat consumption has not always been the same, I think it is nevertheless hardly correct to say, as the author does on page 483, that "the average Willans line as shown in Fig. 15 is almost useless for the purpose of analysis." For instance, the line will obviously give results within the limits of accuracy in fuel analysis if used for estimating monthly fuel consumption for assumed monthly electricity outputs, and will also serve as a useful check on the efficiency of each month's operation. The line as drawn is, of course, bound to give too low a value of fixed heat since the points for small outputs at the left-hand side of the graph include the fixed losses of only one machine while those for large outputs on the right-hand side of the graph include fixed losses for several machines.

The stepped lines shown in Fig. 16 are certainly more nearly true Willans lines; and the line designated "ideal" is, I gather, obtained by adding one after another, in the order of installation, the Willans lines obtained on test for the various machines with, presumably, the minimum possible number of associated boilers. I am not clear as to how the line designated "actual" has been derived since it is apparently not based on the same data as that used for Fig. 15, but, however this may be, I agree that the difference between the heat consumption as given by this line and as given by the "ideal" line does give a measure of the operating efficiency of the station. It is not, however, a "characteristic of the power station," as stated on page 483, but rather a characteristic of its operating conditions. For this reason I think Fig. 17, although correctly derived, is misleading in that it tends to give the impression that operating efficiency decreases with increased plant capacity, whereas there is, in general, no essential connection between these two factors. It might have been better, therefore, to have plotted "operating efficiency" against "year of operation," in order to make it clear that the curve obtained was meant to apply only to the particular station considered during the years stated.

THE AUTHOR'S REPLY TO THE DISCUSSIONS AT LONDON, BIRMINGHAM, AND NEWCASTLE

Mr. F. W. Lawton (*in reply*):

General.

As Mr. Forrest is responsible for the design and operation of the Hams Hall station and is fully acquainted with the subject matter of the paper, his contribution to the discussion is all the more valuable, since it deals with important matters of policy in an authoritative manner, matters which could not well be dealt with by the author.

General Layout.

For Mr. Priest's information the allocation of land to the several works is as follows:—

	Area		
	Hams Hall "A"	Hams Hall "B"	Total
	acres	acres	acres
Buildings	4·05	6·15	10·2
Railway sidings ..	12·00*	48·00*	60·0*
Cooling towers ..	5·75	6·40	12·15
Roads	2·65	2·10	4·75
Gardens	1·10	2·00	3·10
Ash disposal ..	—	—	300·0*
Coal storage ..	8·00	15·00	23·0

Land not allocated = 476·8 acres
Total land purchased = 890 acres
Purchase price = £46 500.

* Available for both "A" and "B" stations.

Buildings.

The building contract for the first section was placed on a lump-sum basis and L.C.C. Regulations were agreed with the contractors, as the local bye-laws were neither so stringent nor so complete, thus control of the works was simplified; moreover, detail drawings were not available at the time of placing the contract.

It is true that great care is necessary in the early stages of superstructure design if ferro-concrete instead of structural steel is used. If properly planned and designed, ferro-concrete construction should be as speedy as structural steel.

The main ferro-concrete superstructure, including the crane rails, will be completely constructed before the turbine beds are commenced, as is the case with structural steel. The essence of the problem is that the entire power-station design must be suited to this type of construction and the foundations and building superstructure so designed that construction can proceed independently of plant fixings. At first sight this seems to be an insurmountable difficulty, but by close attention to design in the early stages this apparent difficulty disappears.

Coal.

Of the 70 collieries from which coal is obtained, only 19 have facilities to accommodate 20-ton railway trucks.

With the construction of the new power station, additional sidings are being arranged, and a capacity of 3 days' supply is proposed.

The suggestion that calorific value figures should be rounded-off seems unnecessary, as this is an approximation that becomes appreciable in heat-balance calculations. Gross calorific values are generally used, but it is the net calorific value that is the true measure of heating value.

In establishing an "order of merit," all costs attributable to the use of a particular coal should, if possible, be ascertained. If, for example, 75 % boiler duty only can be obtained from a given coal, then to the purchase price of this should be added capital charges on 25 % of the boiler plant rendered redundant by the use of such fuel.

Boiler Plant.

The combustion heat efficiency on test of the stoker-fired boilers is 85 %, compared with 86·14 % for the pulverized-fuel-fired units (see Table 17). The combustion-heat efficiency of 79·6 % given in Table 11 for stoker-fired boilers is a guaranteed figure only and includes a contractor's margin rather larger than usual, owing to the character of the basic fuel described on page 472 of the paper.

The remarks on page 473 relating to preheated air for stoker-fired boilers were applicable at the time the station was designed and refer particularly to chain-grate stokers. These are now operating satisfactorily at Hams Hall with preheated air at 320° F.

The heat-efficiency figures in Table 11 are based on the gross calorific value of the fuel and take into account all losses, including radiation and the carbon in the ashes.

Hot-air re-circulation to the air heaters is applied by returning a proportion of the heated air from the preheater outlets to the inlets of the forced-draught fans, sufficient in quantity to raise the temperature of the ingoing air to the air heater to at least 130° F. This has the effect of maintaining the temperature of the air-heater plates above the dewpoint temperature of the flue gases and of keeping them in a dry and clean condition, thereby preventing loss of efficiency and deterioration.

This system has proved completely satisfactory, both on pulverized fuel and with stoker-fired boilers, and no renewals of the air-heater elements have yet been made, although the first five boilers in the station have been in commission for over 10 years.

The heat equivalent of the increase in forced-draught fan-power due to re-circulation is only about 0·05 % of the total heat input to the plant.

The cyclone grit arresters are satisfactory for the stoker-fired boilers, and the cleanliness of the gas emitted from the chimneys is better than the Commissioners' requirements.

Dust-, Grit-, and Ash-handling Plant.

Cyclone grit arresters only were initially installed on the first five pulverized-fuel-fired boilers. Electrostatic flue-gas cleaning was added later to comply with the Electricity Commissioners' recommendations.

On the Hams Hall "B" station electrostatic flue-gas cleaning alone will be used.

Solidification of the wetted ash in trucks is rapid if the water content exceeds 25 %; below 20 % the ash is readily removed from the trucks and without difficulty.

Circulating-water System.

The circulating-water pump casings are of cast iron. No deleterious effects on non-ferrous metals have been observed during 20 years' continuous use of sewage effluent.

The deposit on the condenser tubes is composed mainly of inert organic matter and is easily removed by the passage of a steel-gauze bullet propelled by compressed air through each tube. The number of hours between cleaning varies very widely, being anything between 500 and 2 000 hours, owing to alterations in the constitution of the sewage effluent, which is affected by weather conditions. In general, however, the condensers are cleaned when the back pressure on full output at average atmospheric temperature rises to 1 lb. per sq. in. absolute.

The amount of make-up circulating water is small, representing only about 4·2 % of the total water circulated, and can therefore have little effect on the corrosive properties of the total water circulated. If this water is first passed through the towers it must be pumped up to the discharge culvert and sectionalized pipe lines would be required.

Feed-water System.

One of the duplicate extraction pumps allocated to each condenser is isolated and temporarily arranged to discharge condensate through a measuring tank, from which the water is drawn by the second extraction pump and returned to the system via the feed heaters, the flow being limited to the amount of condensate so discharged, including the stipulated amount of make-up water.

The recognized operating figures are test figures taken in conjunction with observed operating losses such as radiation, etc., and are plotted in curve form (see Fig. 16). The actual test results on the plant are given in Tables 15 to 19 inclusive.

There is no alternative to feed-pump regulation other than to allow the feed pump to run on its characteristic. The latter method is expensive on large installations such as Hams Hall and would dissipate appreciable energy. It is therefore for economy that speed regulation is often chosen. Moreover, a constant feed-water pressure in the feed range is not desirable under all conditions, for at low boiler loads the pressure difference across the feed regulators is too great for satisfactory operation.

The surge valve control referred to was fitted in 1929 and since that time other and simplified devices have been developed.

With regard to the hardness of the make-up feed supply after softening, the figure of 1·0 grain per gallon hardness must be regarded as an extreme maximum, as the usual figure is more in the region of 0·05–0·2 grain.

The quantity of blow-down necessary is largely controlled by the type of feed-water treatment in use and the incidence of condenser leakage, the quality of the make-up feed water being, of course, a contributory factor.

Owing to the purity of our make-up feed supply, the introduction of salts into the feed system from this source is small compared with the quantity of conditioning chemical added plus the effect of condenser leakage; consequently, it is not considered that the substitution of

evaporated make-up for our present system would result in any large reduction of blow-down.

I agree with Mr. Jockel that the concentration of 40–60 grains per gallon of dissolved salts in the boiler water is lower than is usually recommended for our conditions. Whilst it might be possible to operate at higher concentrations, this lower figure is maintained as a means of minimizing carry-over of salts in the steam.

The reason for the adoption of our present system of make-up supply, as opposed to evaporators, is given above.

Under ordinary operating conditions the oxygen content in the feed water is of the order of $0 \cdot 05$ cm^3 per litre, and does not reveal excessive air leakage. Such leakage is indicated if the oxygen content rises to the unusual value of $0 \cdot 1$ cm^3 per litre.

The soft town water used as make-up feed possesses temporary hardness, which results in the presence of sodium bicarbonate in the softened water. No abnormal corrosive effects have been observed in tanks or pipework in contact with this water, nor would such be expected.

The sodium bicarbonate in the make-up feed undergoes decomposition in the boiler, with the production of caustic soda and the evolution of carbon dioxide, which is carried over in the steam. The soda ash used for conditioning the boiler water also suffers the same decomposition, and the evolution of carbon dioxide from this latter source is much in excess of that derived from the bicarbonate in the make-up feed.

No effect definitely attributable to carbon dioxide in the steam has been observed, whilst the concentration of caustic soda is controlled by correct blow-down.

Presumably, by inter-crystalline cracking is meant that type of cracking due to "caustic embrittlement" usually attributed to caustic soda. The conventional method of maintaining a high "sulphate ratio" in the boiler water as a means of preventing "caustic embrittlement" is not employed, but a low caustic-soda concentration is maintained by blow-down control. The whole question of the production and prevention of this phenomenon is a highly controversial one, and the most recent researches of Straub published in 1938 may well result in a considerable modification of ideas on the subject.

Whilst sodium phosphate has, in many instances, proved to be a satisfactory conditioning agent, and perhaps at higher pressures the most satisfactory, its use has been known to give rise to certain troubles such as fouling of feed lines and valves by deposits, "phosphate haze," and production of muds, with a tendency to bake on boiler tubes, and these disadvantages have necessitated its abandonment. Soda-ash treatment has, under our conditions, so far given rise to no difficulties.

I agree that correct conditioning of water is essential in order to prevent scale and corrosion in boilers. With regard to the influence of boiler design on the prevention of scale, it is possible, even with a correctly conditioned boiler water, for scale formation to occur at points of excessive heat transference, which should therefore be avoided in design. Sludge may also accumulate in horizontal parts of tubes or at points of poor circulation and, becoming baked, give rise to exactly the same kind of troubles as scale.

A typical analysis of the sewage-effluent water indicates the total solids to be of the order of 100 grains per gallon. It is not, however, the magnitude of the total solids that causes difficulty when leakage occurs, but their nature. For example, in grains per gallon nitric anhydride exists to the extent of 15, sulphuric anhydride 16, chlorine 14, and free ammonia $0 \cdot 47$.

Dry-bulb temperature, ° F.	55·4	61·75	65·1	69·4
Relative humidity	71·4	81·30	72·2	48·0
Quantity of circulating water, gal. per hr. ..	2 666 000	2 677 000	2 736 900	2 694 300
Temperature of water entering tower, ° F...	91·5	87·80	91·4	91·8
Temperature of water leaving tower, ° F. ..	76·28	74·04	77·66	76·96
Temperature difference, deg. F.	15·22	13·76	13·74	14·84

Erosion is negligible with this water, and with condenser tubes of Admiralty mixture having a trace of arsenic the pitting is slight and compares favourably with other more expensive makes of alloy.

Tests for condenser leakage are made on each condenser when the condenser is down for cleaning, and only in exceptional cases of split tubes is it necessary to take the plant out of service at other times for inspection and test.

A close watch is kept on the conductivity of the condensate.

Cooling Towers

The results of cooling-tower tests under different climatic conditions are given in the Table above.

The weighted average of summer and winter conditions is necessary, particularly if the station is not operating under base-load conditions, where at least one constant can be found amongst so many indeterminate variables. To take into consideration all the possible variables such as atmospheric conditions, wind direction, heat load, water quantities, and steam quantities, would need a whole paper.

If, for brevity, we take a fundamental case, assuming a constant circulating water temperature of 75° F. leaving the towers, a 5 deg. F. temperature difference between the circulating water and the temperature corresponding to vacuum, we have the following:—

Vacuum	Heat load	Relative quantity of circulating water required
in. (Hg.)	° F.	
28	21·1	1
28·2	17·5	1·21
28·4	13·7	1·54
28·6	9·4	2·24
28·8	4·5	4·74
28·9	1·8	11·7

The relative quantity of circulating water required gives some indication of the size of cooling tower necessary; moreover, the cost of pumping 11 times the quantity of circulating water for a vacuum of 28·9 in., compared with 28 in., would go far to offset the thermal advantage so obtained, neglecting the cooling-tower costs which would be prohibitive.

Mr. Martin's remarks do not go far enough. The question of economic vacuum for cooling-tower stations cannot possibly be solved, or even attempted, without the fullest reference to the cooling-tower performance. No improvement in vacuum by reason of increased quantity of water can become final until referred to and allowed for in the cooling-tower system.

Sewage effluent will continue to be used at Hams Hall " A " station; although river water is to be used at the " B " station, it is practically sewage effluent mixed with trade effluent.

Fire-Fighting Equipment.

The only occasion upon which the " Fire-foam " equipment has been required was when an oil-filled reactor burst, and it was then successful in extinguishing the fire. Damage to insulation is more likely to be caused by fire than by the medium used. For the new station, CO_2 for switchgear and emulsified water spray for turbo-alternators are proposed.

Heat Cycle.

If the station were designed to-day the steam conditions would be approximately as for the " B " station, as described on page 491.

I agree that the thermal efficiency is almost independent of the price of fuel, but the economic thermal efficiency is almost entirely dependent on the fuel price allied with load factor.

The Willans line in Fig. 15 is given as an example of its unsuitability for accurate determination of operating results. The ideal Willans line (see Fig. 15) is plotted from test results on all plant summated, to which has been added standby and radiation losses. The actual Willans line has been obtained by plotting actual operating results as each separate machine came into service.

With regard to the operating efficiency curve (see Fig. 17), this gives annual summated results for different plant capacities and it can only be constructed as a power station grows in size, hence its value. When a power station is complete such a curve could hardly be accurately obtained, as the operating period at any given capacity would not be long enough to provide reliable information. The connection between size and efficiency is, however, real and not imaginary, and the observations recorded in the paper leave no room for doubt as to either the reliability or the reality of such a relation.

The object of the remarks concerning load-factor determination in the paper was to direct attention to the importance of accurately calculating this for each particular case if economic design is to be attempted. That much discussion has arisen on this point is gratifying.

Mr. Blackburn's estimate of 70 % for a design basis is nothing more than a scientific guess; it does not bear the laborious marks of careful computation, and, indeed, it assumes that further improvement in heat cycles is well-nigh impossible and that load growth is at an end, truly a pessimistic scientific view with an optimistic load factor as a direct result.

Steam-driven stand-by pumps are included in Hams Hall " A " and are proposed for Hams Hall " B " station. The remarks in the paper concerning steam-driven auxiliaries relate to drives for boiler fans, circulating water, extraction, and other pumps.

The make-up water is not evaporated by bled steam, it is admitted direct to the main condenser.

The falling off in efficiency as the power station grows in size is a function of operation conditions and is largely due to load-curve form which controls the starting up and shutting down of an increasing number of machines, thus increasing the standby losses over what would otherwise be a stable efficiency characteristic.

The average power factors attainable at the generating station under present conditions are as follow:—

Week-day day-time	0·88 lagging
Night-time	0·98 lagging
Saturday and Sunday day-time ..	1·00 lagging
Sunday morning (early)	0·98 leading

but the angle of advance is not sufficient to necessitate special precautions.

The load factor referred to on page 483 is the one used by the Electricity Commissioners in their Reports, this being the source from which the figures were obtained. However, I agree with Mr. Martin that under certain conditions this method of calculating load factor, viz. " units sent out multiplied by 100, divided by the maximum load multiplied by the hours run," can be misleading and, generally speaking, I prefer the method of calculation which has been used on page 475, viz. " units sent out multiplied by 100, divided by plant capacity multiplied by 8 760."

If Mr. Martin will study a typical daily load curve of any power station, he will quickly realize that partial load nozzles cannot be so easily dispensed with; moreover, the operating conditions on a station may vastly change during its economic life, hence if partial load nozzles could be dispensed with under stable load conditions, they would become necessary under unstable load conditions.

The steam conditions assumed for the re-heat cycle mentioned in the paper are:—

Steam pressure, 900 lb. per sq. in. gauge.
Total steam temperature, 850° F.
Approximate additional cost of re-heating equipment, £0·6 per kW of installed plant.
Over regenerative heat cycle at 600 lb. per sq. in., 850 ° F. (See also " Economics of Design.")

Steam Piping.

The case for the corrugated steam-pipe expansion-bends is undoubtedly established where restricted space and low stresses are important. On the other hand, corrugated pipe has a high friction drop, is costly to construct, and tends to whistling and vibration at certain steam speeds.

These considerations have influenced us in choosing

plain bends wherever practicable. In a new layout this is usually a simple matter, and is less costly if due regard be paid to the arrangement of expansion loops.

All costs of steam feed and water service and fire hydrants are included in the total capital costs, but the item "Steam and water pipes" in Table 7 does not include feed mains and feed-water pipes associated with the closed feed-water system, the cost of these pipes and valves being included under "Turbo-alternators and condensing plant" in the same Table.

Main Turbo-Alternators.

The capital and fuel savings arising from the use of 33 000-volt alternators, as compared with 11-kV alternators and step-up transformers, are small. For example, considering the present Birmingham system, where generation at 11 000 volts through step-up transformers to 33 000 volts, for transmission over an average distance of 10 miles already exists, this system can be used as a basis of comparison for the following alternatives:—

	Saving (£ per annum)
11-kV generation, 33-kV transmission ..	basic
11-kV generation, 66-kV transmission ..	6 470
33-kV generation, 33-kV transmission ..	13 700

The practical advantages of 33-kV generation and transmission, so far as Birmingham is concerned, are:—

(*a*) With 33-kV transformer, 20 000 kVA is carried on each cable. This capacity suits the loading on the main distribution centres better than 66-kV transmission, which results in 40 000 kVA per cable.

(*b*) The absence of large step-up transformers in close proximity to the power station is a fire risk that is best avoided, particularly from the point of view of air raid precautions.

With the exception of advantage (*b*), the above considerations are entirely local and are therefore not applicable to other systems where 11-kV generation and 66-kV transmission over longer distances may well be economically justified if more-heavily-loaded distribution centres are required.

The method used by Dr. Garrard when calculating the surge voltage between adjacent conductors of high-voltage alternators of the concentric conductor, and also of the normal lap-wound type, is based on the supposition that the capacitance between adjacent conductors is small in relation to that to earth, so that the surge energy must pass through the windings.

While this assumption is reasonable for an alternator of normal construction, it is not correct for the concentric-conductor type of winding where the capacitance between the bull, inner, and outer conductor in a slot is high compared with the capacitance to earth of the bull conductor. In consequence an alternative path of a much lower impedance is provided for the surge and, as the capacitance between sections is about equal, approximately one-third of the applied impulse voltage appears between each of the conductors irrespective of the length of the wave-front, i.e. the surge voltage is uniformly distributed throughout the winding under all conditions.

The ratio of the surge voltage to the operating voltage between sections of the winding is therefore the same as the ratio of the applied impulse voltage to the operating voltage of the alternator. With the ordinary type of winding having more than one turn per slot, the ratio of the surge voltage to the normal working voltage between turns may be much increased.

Additional advantages of the concentric-conductor alternator are the absence of oscillations within the windings, in consequence of the uniform initial distribution of surge voltage, and the low surge impedance resulting in marked attenuation of the surge in the winding.

The typical impulse-voltage distribution in a concentric-conductor high-voltage alternator and, for comparison, in a transformer was given in the reply to the discussion on a paper on "Direct Generation at High Voltages" by J. Rosen at the International High-Tension Conference in Paris, 1937.*

The ability of the concentric-conductor high-voltage alternator to withstand severe operating conditions without special surge protective gear has been demonstrated by tests and by the satisfactory performance of the numerous alternators now in commercial service.

This view is also held by independent investigators. In a paper by J. F. Calvert† on cathode-ray oscillograph studies of the penetration of surge into machine windings it is stated that: "The protection of the turn insulation should be considered next. The winding using concentric turns (one actually inside another within one slot), which was introduced in Europe for high-voltage machines, should give adequate protection to the turn insulation."

Auxiliary Circuits.

Protection against the effects of external faults is important. Mr. Forrest dealt with one aspect of this in his contribution.

Where auxiliary motors are supplied from the main busbars through house transformers, a sustained short-circuit such as may occur due to a busbar fault would dislocate the auxiliary motors; it is for this reason that unit generators are preferred to unit transformers.

If all pulverizer and boiler-fan motors are supplied from the external circuit through step-down transformers external interruption would cause stoppage of these motors, resulting in a fall of steam pressure so rapid that load-shedding could not save the station from falling out of synchronism with the healthy external circuit.

In the case of the Hams Hall "B" station, the direct-coupled generator on each main alternator shaft will together be sufficiently large to supply all auxiliary motors which have to be operated in connection with the plant, thus increasing the margin of safety in the event of external electrical disturbances.

With the end-on arrangement of turbo-alternator as adopted at Hams Hall, the extra length of the machine due to the direct coupled auxiliary generator does not necessitate more building accommodation, because with a single row of boilers the distance between adjacent machines is sufficient to house the auxiliary generator.

Dr. Kahn has made some interesting suggestions relating to d.c. auxiliary drive and, if it were necessary for all or the majority of motors to have speed variation, there is much to be said for the proposals. Actually, the

* *C.I.G.R.E. Compte Rendu*, session 1937, vol. i, p. D11.

† "Protecting Machines from Line Surges," *Transactions of the American I.E.E.*, 1934, vol. 53, p. 139.

only motors requiring speed control are boiler-fan motors and feed-pump motors, and this can be effected either mechanically by hydraulic couplings, or electrically by a.c. commutator motors, a comparatively recent development. These motors represent approximately 10 % of the total number of motors required in a power station; hence 90 % can be a.c. motors. It is recognized that these motors are both cheaper to install and maintain than d.c. motors, hence the reluctance to use the latter unnecessarily.

The use of mercury-arc rectifiers to supply shunt-wound d.c. motors is quite satisfactory from a technical point of view.

Investigations relating to Hams Hall "B" station have shown that the chief advantage of higher-voltage electrical auxiliaries is the reduction in size of the cables to motors, particularly in the boiler house, but no appreciable saving in cost can be shown.

Step-down transformers are also proposed for the smaller motors, and direct switching is proposed for motors smaller than 90 h.p.

The d.c. busbars are energized normally by the house turbo-generators, and the motor-generators are of the induction type. The 1 500-kW a.c. generators are wound for 440 volts and not 3 000 volts; the latter voltage is proposed for the new station.

The capacity of the auxiliary generators was limited to the capacity of what were considered to be the essential motors. It is, however, proposed to increase the direct-coupled generator capacity at the new station and so reduce the effects of external electrical faults.

Control Room.

Proposals for automatic boiler control have been investigated and, owing to the fact that Hams Hall station was intended to operate under base-load conditions, automatic control could not economically be justified.

Automatic boiler control is not proposed for the new power station, but technical control of the whole power station from the main control room is arranged and consists of shadowgraph instruments indicating boiler-steam flow, temperature, and pressures, and flue-gas temperature, as well as turbine-steam flow, temperature, pressure, and back pressure.

The reasons for adopting a control room remote from the power station are:—

(*a*) Regulations under air raid precautions.

(*b*) Detachment of control engineer from noise and turmoil of the power station.

For the new station the control room will be circular in plan, with shadowgraph instruments mounted on small panels, and with desk-type operating equipment. Marine-type signalling will not be repeated.

Main Switchgear.

The switchgear proposed for the new power station is of the indoor metalclad single-break type, with small oil content, and will have a rupturing capacity of 1 500 MVA. The busbars will be of the gas-filled type.

Transformers.

The efficiency of modern transformers is, as Mr. Charley rightly says, remarkable and represents a worthy engineering achievement. The proper appreciation of transformer efficiency and indeed qualities of design and construction by power-station designers is often clouded by the operation of ring prices, which seem to make almost uniform both price and efficiency of this important unit. When the true efficiencies of transformers are declared with the true cost of manufacture, consideration of the merits of the transformers offered will become easier of assessment.

The first part of my reply under the heading "Main Turbo-alternators" is relevant to the choice of switching voltage and disposes of the problem of selecting either 66-kV or 132-kV switchgear. Local conditions and not technical considerations are often the controlling factors in such a choice.

Works Cost.

No claim is made that low-grade fuels necessarily mean low works costs. The function of economic design is surely to attain the lowest works costs possible in the locality where the power station is to be established.

The operating efficiency of a station using coal at 13s. per ton ought to be much higher than another using coal at 9s. 6d. per ton, load factors being equal. If this is not so, it suggests that the design is casual and not based on economic principles.

The capital costs given in Table 7 do not include capital charges incurred during the time when the station was under construction.

Load Curves.

The reason for the similarity between the summer and winter curves for 1935 is that at this time the capacity of the station was sufficiently small for it to be run as a pure base-load station, thus giving a nearly uniform output through the year.

The construction of the curve shown in Fig. 17 is explained on page 483 of the paper; its slope is a measure of the total stand-by losses that increase with the number of sets installed and are incurred more frequently as the station load follows an increasingly irregular demand. With a stable demand the curve would be less steep, but it can never be horizontal as Mr. Dalman's question suggests.

This answers Mr. Martin, who raised a matter of efficiency variation, using test figures only as a basis of comparison. The practical aspects of operation and load variation account for the missing 2 % heat loss, much of which over the period mentioned was absorbed in drying out machines and running up new plant.

Transmission.

The transmission costs from Hams Hall "A" station to the city are as follows:—

Annual charge per kVA of trunk capacity, 5s.
Cost of losses per unit transmitted, 0·0094d.

These costs are based on a 15 000-kVA trunk operating at 30 % load factor and they include for the necessary transformer at either end.

The 33-kV system is not interconnected, hence no difficulties are likely to arise owing to the use of the 200-ampere earthing resistance.

Economics of Design.

Mr. Clinch has apparently misunderstood the paragraph he quoted. Power-station economics and coal conservation are not synonymous.

If coal conservation is of itself the important factor, then the highest thermal efficiency attainable, irrespective of capital charges, is the only answer. This is clearly a reversal of the present tendency towards economic design, where the value of efficiency attainable is balanced against the capital and operating costs of the plant necessary to attain this efficiency.

Thus the efficiency is limited by economic considerations and is not permitted to become a matter of engineering technique alone.

In reply to Mr. Dollin, the relatively few principles common to all power stations refer to location, load demand, and local conditions, including characteristics and price of fuel. The principles of thermodynamics and of economics are of course common to any power station, it is the application of these principles which varies so widely.

The standardization of, say, steam conditions or of generation voltage would not be consistent with economic results. In all cases local conditions should be taken into account and allowed to play their part in such determinations.

Personnel.

Mr. Mitchell's difficulty is self-created, for we have found no such difficulty in working the manual-training scheme. The practical and written test applied to would-be drivers and stokers is such that a long experience is required before a pass can be secured; moreover, success in the oral test for initiative in emergency and personality means that a full pass can only be secured by a man of outstanding ability. Such men have the advantage of working when required as standby drivers or stokers and are paid full rates while on such duties. We have not a large number of certified men awaiting promotion, but we have sufficient to keep pace with our retirements and growing demand.

A REVIEW OF THE DESIGN AND USE OF POTENTIOMETERS

By D. C. GALL.*

(*Paper received 4th January, and read before the* METER AND INSTRUMENT SECTION *3rd March,* 1939.)

SUMMARY

This paper deals with the circuits in direct-current potentiometers and details of their construction and use. The elementary circuits are first described, followed by the more elaborate ones necessary for precision potentiometers. Thermo-electric effects and other sources of error and methods of obtaining true zero are considered. Some practical details in the accurate measurement of current and voltage are discussed, as well as the devices used for these purposes. The special form of potentiometer used as a voltage standardizer is described.

The basic idea of the potentiometer is so simple that it appears hardly to justify a description, but when the subject of measurement with the potentiometer is approached more closely a number of practical details obtrude to complicate matters. The object of this paper is to deal with some of the practical difficulties encountered in designing, constructing, and using potentiometers and to describe the principal classes into which they fall.

The simplest potentiometer consists of a slide-wire through which a current is flowing from a battery. There is a voltage-drop along the wire, any portion of which can be tapped by means of the slider. Thus a continuously variable value of potential is available as the slider moves from one end of the wire to the other. The magnitude of this potential will be given by the product of the current in the wire and the resistance between the end of the wire and the slider; that is, between the potential points. The voltage-drop along the wire is most conveniently standardized by balancing against a standard cell through a galvanometer. This balance is for convenience made by adjusting the current from the battery when the slider is set to a scale value corresponding to the known voltage of the standard cell. In this way the scale of the slide-wire reads directly in volts. This is the basic idea of the simple potentiometer shown in Fig. 1.

A standardized potential gradient having thus been set up, any unknown voltage within the range of the voltage-drop can be determined by simply balancing it by means of the galvanometer, by moving the slider until the galvanometer shows no current to be flowing and therefore no difference of potential to exist between the unknown voltage and the voltage-drop on the wire. Simple as the process is, it took about 50 years to evolve from its first conception.

Simple slide-wire potentiometers have been used by students for many years. They consist usually of a bare resistance wire stretched on a board with a scale of millimetres to indicate the position of the sometimes crazy slider. It is often considered a good exercise for confusing students to use an arbitrary scale instead of making the divisions direct-reading in volts, but the author has always disliked this principle of education and has therefore constructed scales which are 1 200 mm. long so that the standard cadmium cell with its value of 1·018 volts can be balanced at its appropriate value and thus make the scale direct-reading (1 mm. corresponding to 1 mV).

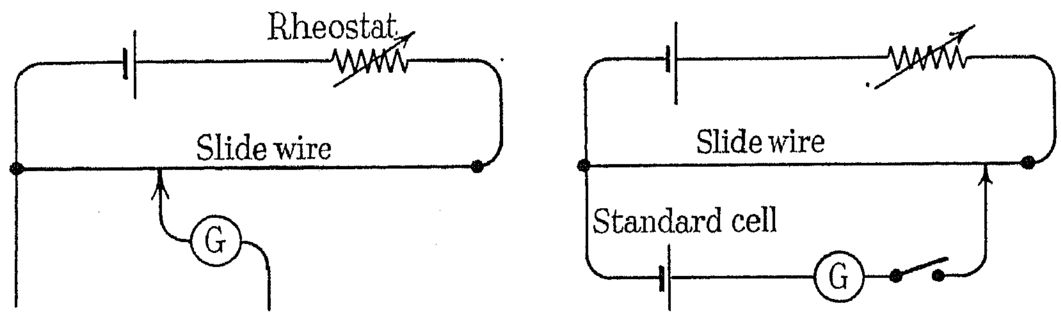

Fig. 1

It is important that an instrument for measurement should indicate what it measures, and in all potentiometers of higher precision this is carefully considered in the design. The author's sympathy for the student tormented by a slider which often failed to make contact, and only worked when pressed hard on the wire, led to the design of the simple geometric slider shown in Fig. 2. It keeps its parallelism in the V grooves and rubs surely but resiliently on the wire. The contact cannot be pressed into the wire—the frequent cause of kinks and uncertain contacts.

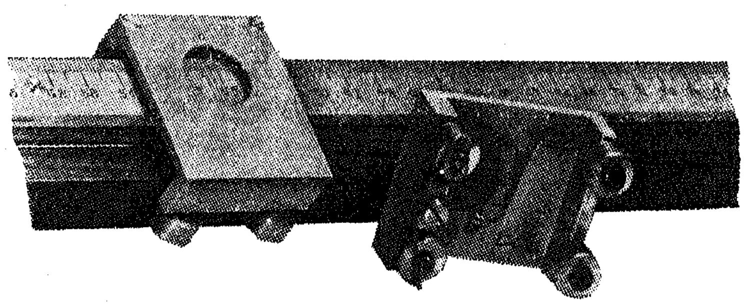

Fig. 2

* H. Tinsley and Co.

A 1-m. wire subdivided into millimetres gives an apparent degree of subdivision of 1 in 1 000. In practice the uniformity of the cross-section and therefore the resistance gradient of the wire may vary by 1 in 100. Thus the uniformly divided scale will not be a true voltage scale. Either a calibrated scale or a table of corrections will be necessary.

In practice the simple exposed slide-wire does not really justify either of these expedients as an industrial

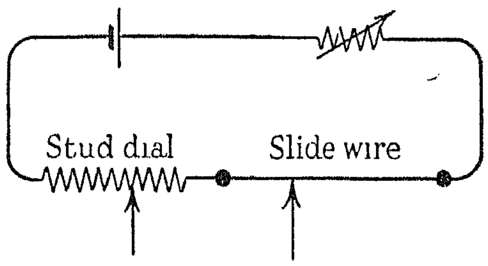

Fig. 3

instrument, and when an accuracy of better than 1 % is required a sounder plan is to use a 2-dial instrument in which the slide wire forms only part of the reading. The scheme is shown in Fig. 3. The simple expedient of putting a set of coils of equal resistance in series with the slide wire at once increases the accuracy in proportion to the number of coils.

Long slide-wires correctly designed can be made to give extremely precise potential-gradients, but they then become of an entirely different type from the simple exposed wire, and the practical applications are very limited. Long exposed wires suffer from mechanical damage, corrosion, irregular scale law, uneven wear, variations of length and resistance with temperature, and contact-resistance troubles. Thus short slide-wires covering only a limited part of the voltage-drop are preferable, and in circular form are much more compact and more easily stretched and kept uniform. The materials available for slide-wires are limited because it is necessary to have a reasonably non-corrosive metal of low temperature-coefficient and good wearing properties.

Platinum-silver alloy is very good except for temperature coefficient. This is of the order of 0·04 %, so that a change of 10 deg. C. will alter the voltage-drop on the wire by 0·4 %. This might be a serious error even in a 2-dial instrument. The temperature coefficient can be reduced by shunting the wire by a manganin shunt. This is usually done, but necessitates a finer and less durable wire. Eureka (a copper-nickel alloy) has all the required properties, but unfortunately it has a very large thermo-electric effect against copper. This may easily introduce stray voltages into the measuring circuit. If the slider is moved vigorously on a eureka slide wire, a galvanometer across the potential circuit with no battery connected will be deflected by the thermo-electric effect, which may be many microvolts. This false voltage acts directly in the galvanometer circuit when the slider is moved. The effect can be very much reduced by using a slider of the same material as the wire and sufficiently long to prevent the heat of friction reaching the junction

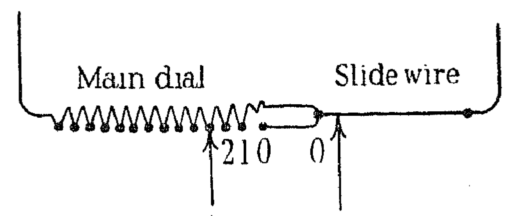

Fig. 4.—Device for obtaining true zero.

to the copper wire. It is seldom practicable to use eureka wiring throughout the circuit. Plated manganin has been used, but the protective plating can cause thermal e.m.f.'s which nullify the advantages of the material.

The presence of thermo-electric effects in the galvanometer circuit produced by operating the dials of the potentiometer is one of the first practical difficulties encountered. Their importance is, of course, greater with the measurement of small voltages. Another difficulty is that of zero. It is very difficult to get the slider to travel to the very end of the slide-wire, and when there is more than one dial obviously the two potential points cannot be coincident, so that there is always a little resistance between the potential points, and this limits the smallest voltage value which can be measured. The method of overcoming this in a 2-dial instrument is shown in Fig. 4. A potential lead is taken back to the " 0 " stud of the dial from the end of the wire, so that these two points are at the same potential. A still better scheme is that shown in Fig. 5, which gives a zero point a little way along the slide-wire and therefore a few divisions of negative value. The current is led into the slide wire from the " 1 " stud of the dial. The slide-wire is shunted by a " tapped " shunt, and the adjustments are such that the voltage-drop up to the tapped point is equal to one stud. Thus the zero point on the slide-wire is opposite the tapped point of the shunt. To the left of this the voltage will be negative, and to the right positive, as in the previous cases.

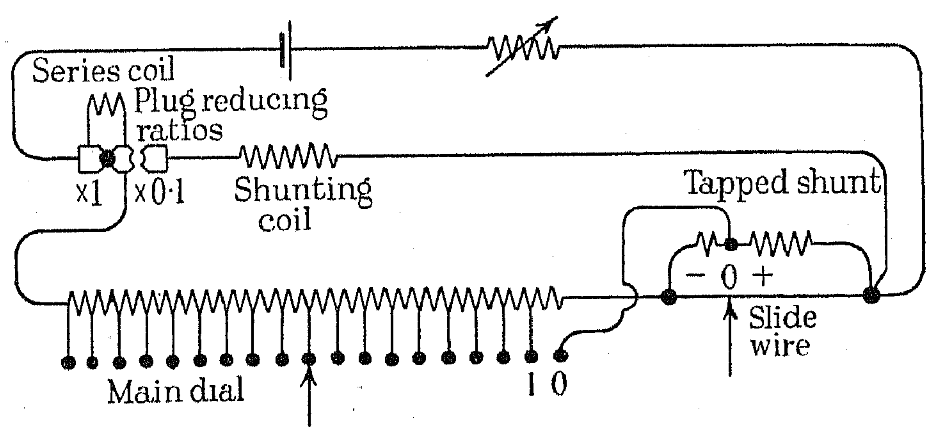

Fig. 5

Unless it is possible to measure down to zero, it is almost impossible to realize the full precision of the instrument when small parasitic voltages are present in the circuit. By disconnecting the supply to the circuit under test the presence of parasitic voltages can be readily observed. The potentiometer should balance at zero. If it does not, a voltage is present which is not due to the supply. If this is steady, it can be measured and allowed for. It may have a negative value, in which case the above scheme facilitates measurement. Another method is to reverse the polarity of both the potentiometer battery and the supply, and take the mean of the readings. This is quite accurate so long as the extraneous voltage remains unchanged. This is not always the case with thermo-electric effects due to self-heating.

A 2-dial instrument consisting of not less than 10 steps in the first dial and a long slide-wire for the second is capable of a degree of subdivision of 1 in 10 000. If the first dial consists of 100 steps and the slide-wire is accurately subdivided, a still higher degree may be obtained, but slide-wires are not recommended for precision potentiometers. Two series dials of 100 studs each

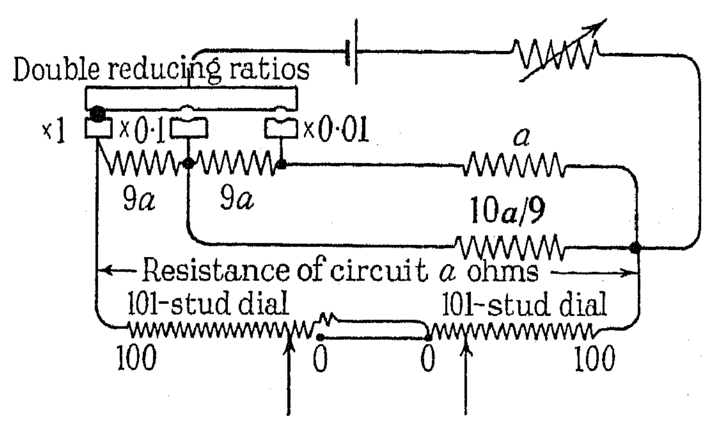

Fig. 6

will give a degree of subdivision of 1 in 10 000, and as each coil can be accurately adjusted each step of the last dial will be more accurate than an estimated position on a slide-wire scale, so that interpolation between studs by galvanometer deflection can be used for further subdivision. This is probably the best combination which can be devised for simplicity, accuracy, and speed of operation. Fig. 6 shows a potentiometer with this arrangement. It has the virtue of a true zero, a very small internal thermo-electric effect, and three ranges. The three ranges are obtained by shunting the dials and introducing a network of resistances to keep the resistance the same, by the operation of a single plug (shown schematically in Fig. 6). An alternative method is shown in Fig. 7. Thus the potentiometer reads, on the three ranges,

1 volt in 10 000 steps of 100 microvolts,
or 0·1 volt in 10 000 steps of 10 microvolts,
or 0·01 volt in 10 000 steps of 1 microvolt.

The stud contacts and contact arms are of silver-gold alloy. This has a very small thermo-electric effect against brass, so that the most vigorous rotation of the dials cannot produce more than $0 \cdot 2\,\mu V$ at the contacts. The circuit for balancing the standard cell is not shown in Figs. 6 and 7, for simplicity, but is similar to Fig. 10.

When still further degrees of subdivision are required simple series dials cannot be used. It would, for example, require 1 000 studs on one of the dials to increase the order of subdivision of the previous potentiometer. Lord Rayleigh devised a beautifully simple method of unlimited subdivision by putting two resistance boxes in series and increasing on one and decreasing on the other,

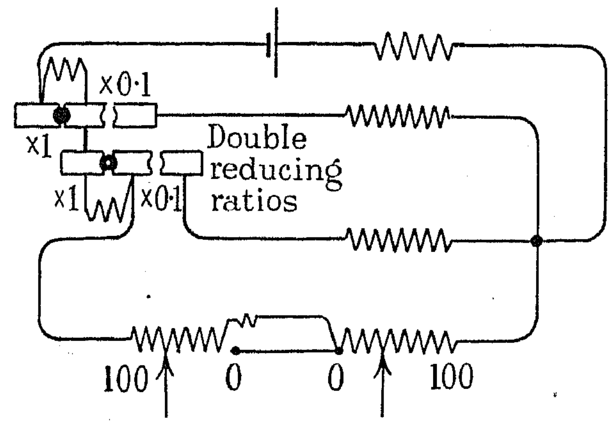

Fig. 7

keeping the total resistance constant and using the voltage-drop across one box. It is obvious that there is no limit to the number of dials the boxes can have in theory. In practice the limit is soon reached, owing to the variation of the contact resistances. The practical application of this principle is the Feussner potentiometer shown in Fig. 8. This combines both the series dials and the Rayleigh constant-resistance or substitution circuit. One of the resistance boxes is placed between the two potentiometer dials; the other, mechanically coupled to the first, is in series to keep the circuit resistance constant. In order to eliminate the effects of contact resistance a high circuit resistance is used. This greatly limits sensitivity of the galvanometer but helps to achieve a reasonably low zero. A true zero cannot be obtained, because of the residual resistance between the potential points.

A better method of obtaining a high degree of subdivision is based on the Varley vernier principle, but this device also is not without defect. It consists of a vernier dial shunting any two steps of the main dial and thus providing a travelling potential tapping-point between the studs of the main dial. Fig. 9A shows the scheme. In simple theory the resistance of the vernier dial is equal

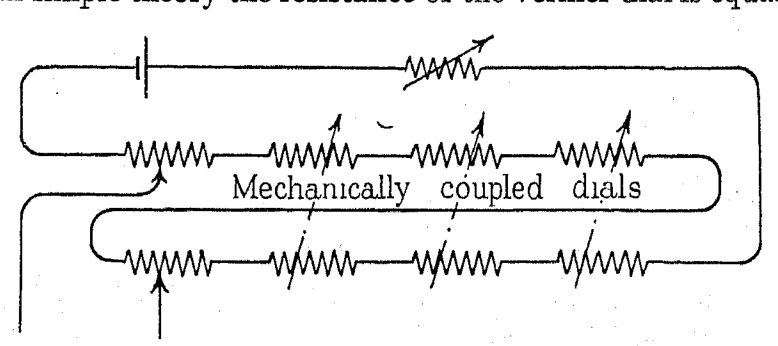

Fig. 8

to two studs of the dial it shunts, so that in effect the combined resistance is reduced to that of one unshunted step. The voltage-drop across the two shunted steps and consequently across the vernier dial is therefore the same as each unshunted step. This voltage-drop can be subdivided to any degree by the number of studs on the vernier dial or by further vernier dials.

Theoretically there is no limit to the number of vernier dials, but in practice the limit is soon reached by the resistance becoming comparable to the contact resistance. The resistance of the dial steps goes down rapidly. If each step of the first dial is 10 ohms and each vernier dial

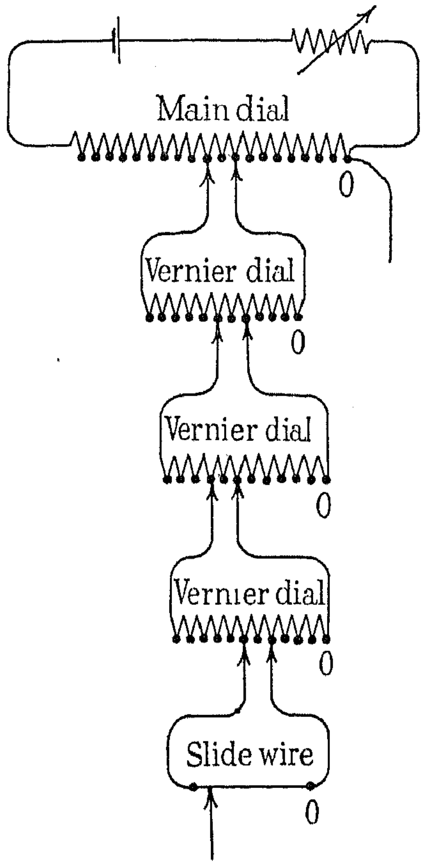

Fig. 9A

has 10 steps (that is, 11 coils): The resistance of each coil of the first vernier will be 2 ohms, of the second vernier 0·4 ohm, of the third vernier 0·08 ohm, and of the fourth vernier will be 0·0016 ohm. In other words,

potential divider shown in Fig. 9A, which is a type used for fault localization on cables.

In practice, the resistance of the vernier dial must not be made equal to that of the two steps in shunts. This is because the potential point on the vernier dial cannot be coincident with the studs on the shunted dial. The resistance of the vernier dial must be higher than its nominal value, to give correct values of potential, otherwise the voltage-drop along the coils of the vernier dial will not correspond to one stud of the dial it shunts.

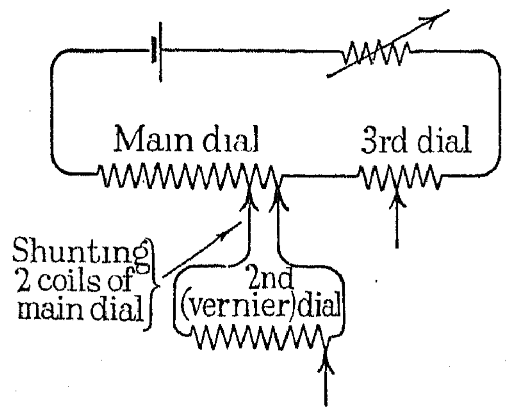

Fig. 9B

Variations of the contact resistance limit the accuracy of the vernier dial. In a precision potentiometer this effect may be serious. To overcome this the author has modified Varley's arrangement, and now uses a higher-resistance vernier dial, as shown in Fig. 10, thereby reducing the effect of any contact variation and obtaining a low zero. Potentiometers are extremely easy to check, if two are available. The second instrument need not be accurate but must be finely adjustable and stable. The process of checking simply involves a comparison of the voltage-drop upon successive steps. For example, to check the main dial, set this at "1" and the dial below

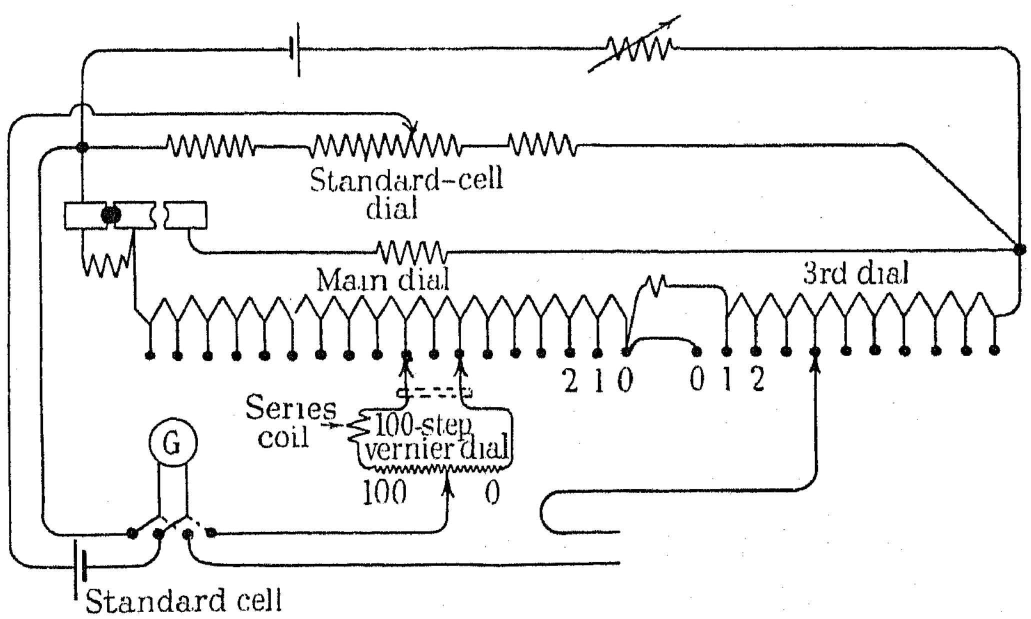

Fig. 10

each resistance is one-fifth of the previous one. The varying resistance of the contacts which connects the vernier dial to the studs which it shunts would nullify any further attempt at subdivision. In practice, only one vernier dial is desirable in a relatively low-resistance precision potentiometer as shown in Fig. 9B, although more may be used with advantage in the high-resistance

it at "0." Balance the voltage by the second potentiometer—its reading is immaterial. Now change the main dial to "0" and the dial below to "10." The voltage should be unchanged and the second potentiometer still in balance. If it is not, the change of balance is the error between the first step of the main dial and the total of the second dial. The process can be con-

tinued by re-balancing at " 1 " on the main dial and " 10 " on the lower dial, and so on.

A means of obtaining a true zero on a potentiometer with a vernier dial puzzled the author for many years, until he devised the scheme (shown in Fig. 11) of using an entirely separate circuit for the third dial. By proportioning the resistance of the circuit the zero can be made at any point on the last dial, allowing a negative as well as a true zero value. An additional dial has recently been introduced into this circuit to extend the subdivision of the potentiometer to 1 part in 10^6. This constitutes the highest degree of subdivision attempted in a precision instrument, and the circuit was chosen after much consideration as being the most suitable from all points of view.

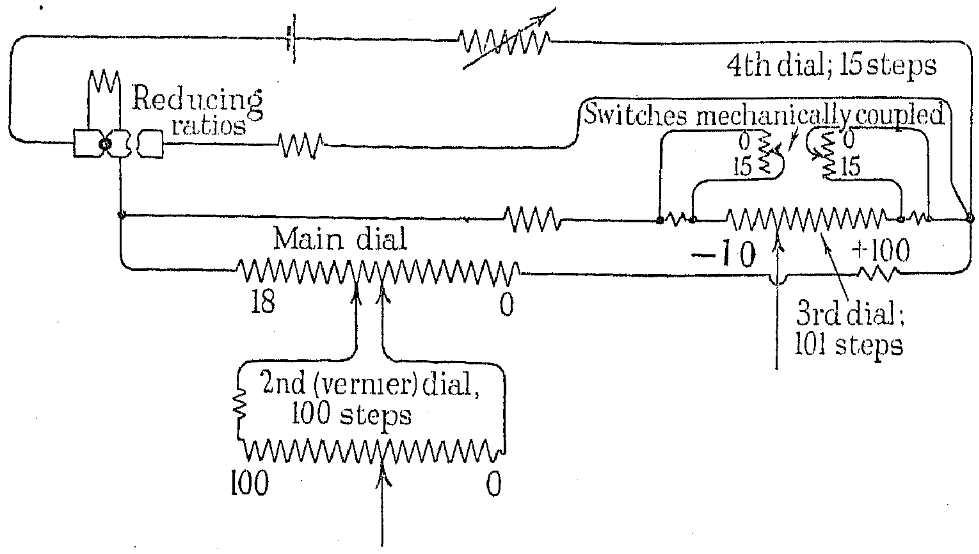

Fig. 11

A point of importance is convenience in standardizing the potentiometer against the standard cell. The most straightforward method is to set the dials to the value of the standard cell and adjust the battery current until the potentiometer balances the cell, thus ensuring that the dial readings are true values. This, while being the most accurate method, is inconvenient in practice as it involves resetting the dials whenever it is desired to check against the standard cell, and this should frequently be done during use. For quick working it is preferable to be able to check the standard-cell balance by merely turning a switch and without altering the setting of the potentiometer dials. The simplest circuit for such a purpose is an entirely separate parallel circuit such as is shown in Fig. 10. The selector switch transfers the galvanometer to this circuit, and when the voltage-drop in this circuit is correct the voltage in the main potentiometer will also be correct. A dial allows this circuit to be set to various standard-cell values.

For the measurement of very low voltages (fractions of a microvolt) rather special attention must be given to the thermo-electric effects in the potentiometer circuit. Sliding contacts in the potential circuit cannot very well be used, and every junction in the potential circuit must be suspect. The galvanometer itself may have dissimilar metal junctions and must therefore be kept free from temperature-changes. Brass terminals are not advisable, and copper should be used throughout.

The Diesselhorst potentiometer is one of the best examples of a circuit designed to eliminate the thermo-electric effects in the potentiometer circuit itself. This instrument has 5 decade dials, giving a degree of subdivision of 1 in 10^5, and the lowest step is frequently set to be $0 \cdot 1\ \mu V$. The schematic diagram of the circuit is shown in Fig. 12. The potential points are fixed and al dial movements are in the current circuits, so that the thermo-electric effect brought about by a switch movement is in series with the battery and not the galvanometer. In the case of the first dial the battery points are simply moved along the circuit by mechanically-coupled switches. Thermo-electric effects due to movement of the switches will be direct additions to the battery voltage, producing thereby an effect which is only

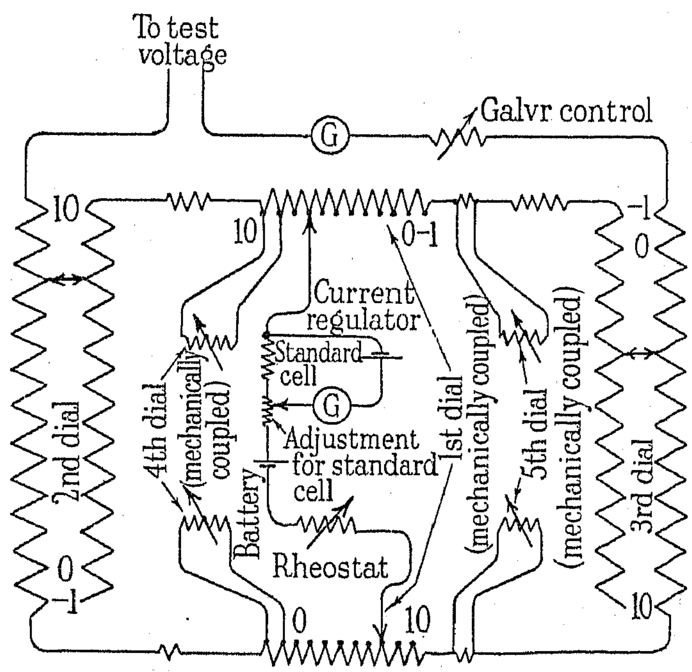

Fig. 12

of the order of parts in a million. The second and third dials are Rayleigh substitution circuits; the thermo-electric effect due to switching is in series with the current circuit and can only change the current by a minute percentage. The fourth and fifth dials are high-resistance shunts on 1-ohm coils, so that the thermo-electric effect is acting in a high-resistance circuit tending to change the voltage-drop on the 1-ohm coil. Under the worst conditions this change cannot exceed one-hundredth part of the thermo-electric voltage.

This type of potentiometer is very popular on the Continent. Its low resistance in the galvanometer circuit makes it sensitive for low-voltage measurements, but it is less suitable for voltages above a maximum of 0·1 volt. For use up to 1 volt a 10-volt battery is required, which limits the application of the potentiometer to general measurements. Moreover, it is not easy to adjust the odd-valued coils to the very high degree of accuracy which the degree of subdivision of the potentiometer demands. It is much easier to adjust and check the vernier type of potentiometer circuit shown in Fig. 11, because all the coils are of equal value and the dials are adjusted to be in correct step by independent coils.

The sensitivity of the galvanometer depends upon the combined resistances of the circuit across its terminals. If this resistance varies with different settings of the potentiometer dials, e.g. increasing as the potential points are moved to positions of greater voltage-drop, the sensitivity for a given out-of-balance voltage will vary. This is of no great importance if the galvanometer is sufficiently sensitive to detect the lowest required voltage

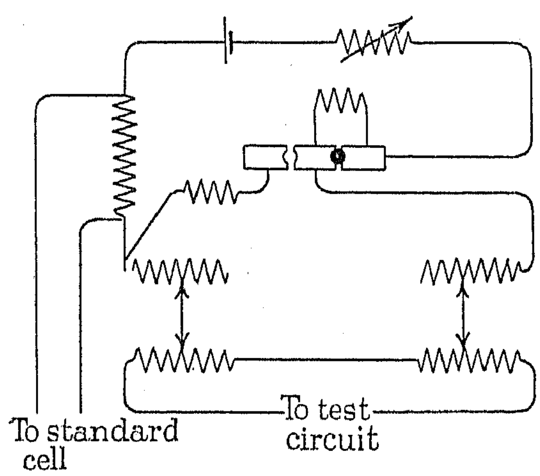

Fig. 13

in the highest-resistance external circuit. But if the potentiometer is so designed that the resistance in the galvanometer circuit is constant, the deflection will always be the same for the same out-of-balance voltage. The deflection of the galvanometer can by this scheme be made to subdivide the lowest steps of the dials and give a very quick and accurate measurement of the voltage under test. This need not be exactly balanced; its value can be read partly upon the dials of the potentiometer and the remainder by the deflection of the galvanometer. Various schemes for keeping the galvanometer-circuit resistance constant have been devised. The Carpenter–Stansfield circuit shown in Fig. 13 is one of the simplest. This is mostly used for thermocouple work. The resistance of the thermocouple is usually small. The deflection of the galvanometer must be calibrated for one step of out-of-balance voltage. A series resistor can be used to bring the deflection to a convenient round figure, so that, for example, 1 mm. on the scale corresponds to 1 μV. Deflectional potentiometers are very convenient for making observations on changing quantities such as those in connection with cooling curves.

Another type of potentiometer is the self-balancing type in which deflections of the galvanometer bring about the automatic balancing of the voltage. The Callendar recorder was one of the first instruments of this type. Contacts operated by the displacement of the galvanometer caused clockwork to move the slide of the potentiometer wire until the galvanometer was in balance. A record of the position of the slider and thus of the voltage was automatically traced. The semi-automatic potentio-

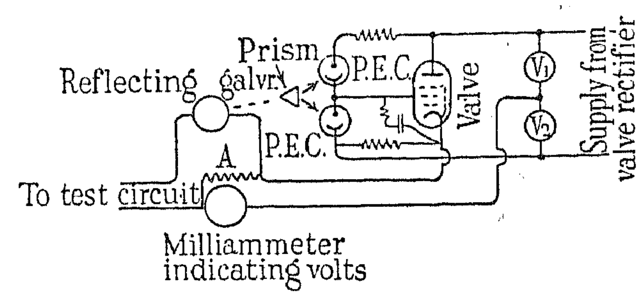

Fig. 14

meter* used for thermal analysis is a further special, but similar, type.

A recent form of self-balancing potentiometer is the Weston No. 721 model. This instrument is automatic and almost instantly balances the unknown voltage. A reflecting galvanometer deflected by the out-of-balance current acts upon two photo-electric cells in conjunction with a pentode valve. The scheme is shown in Fig. 14. The out-of-balance current causes either one or the other photocell to apply voltage to the grid of the valve. The effect is to cause current to flow through a milliammeter into the resistor across which the unknown potential is applied until the galvanometer is balanced. The voltage-drop on the resistor automatically balances the voltage applied to it. The value of the unknown voltage is indicated by the milliammeter. It will be noted that the action is quite different from that of a valve voltmeter, and the accuracy is governed only by the milliammeter and the resistor A, not by the valves or photocells. This apparatus operates from the a.c. mains.

For use in the measurement of small voltages such as occur in temperature measurements, a large number of significant figures may not be necessary, but the value to the nearest fraction of a microvolt is required. For such measurements very simple circuits can be used. If a

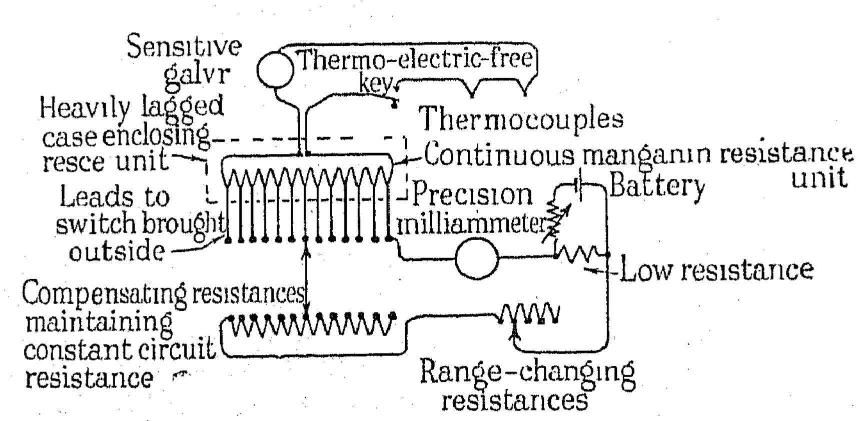

Fig. 15

voltage-drop is produced upon a fixed resistance of low value by the application of a measured current through a circuit of relatively high resistance, no thermo-electric effects will appear across the low resistance, so long as the two extremities are at the same temperature. The scheme shown in Fig. 15, using a magnanin resistor

* R. J. M. Payne: *Journal of Scientific Instruments*, 1935, vol. 12, p. 348.

with tappings at which the current enters, and a compensating series resistor, is one of the simplest. The voltage can be determined from the current flowing in the circuit and the resistance of the tapping point on the manganin. The resistance unit is heavily lagged to reduce temperature effects.

Switches made of copper throughout are very free from thermo-electric effects. The "dual" contact type of switch is very good in this respect because its contacts maintain very uniform temperatures, especially if they are oil-immersed. Fig. 16 shows a copper switch of the type in which the maximum thermo-electric effect brought about by vigorous operation does not exceed $0 \cdot 01\ \mu V$.

Currents are measured by the voltage-drop upon a standard resistance, commonly called a shunt. A shunt for this purpose should be of accurately known value, and permanent. It should also be free from thermo-electric effects. This almost necessitates the use of a

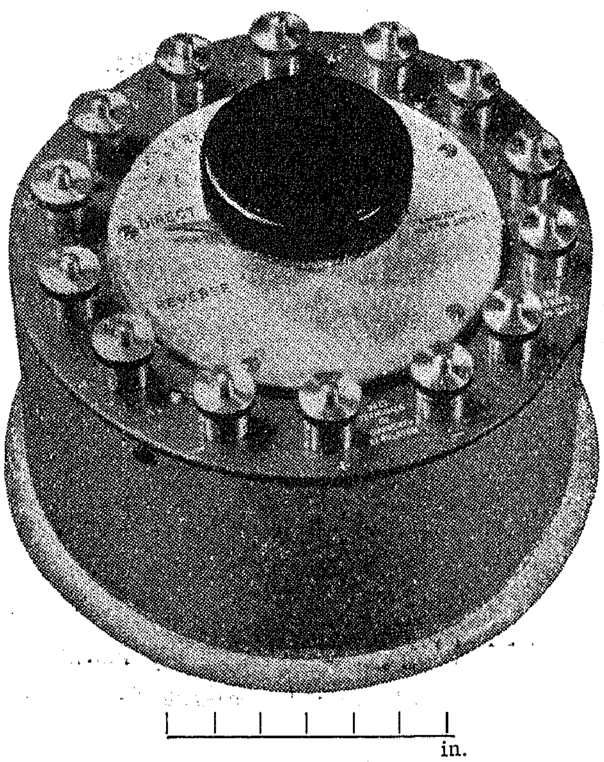

Fig. 16

manganin type of alloy for its construction, because no other common resistance alloy has such a low thermo-electric effect against copper (of which the leads will be made) nor such a low temperature-coefficient.

Air-cooled shunts are cleaner than oil- and water-cooled ones but do not dissipate their heat so well, so that when a large current and large voltage-drop are required the more complicated construction of the latter type may be more economical. The advantage of a large voltage-drop is ease and accuracy of measurement. Thermo-electric and other stray effects are correspondingly less important. On the other hand, a large voltage-drop means higher cost and greater bulk. For very accurate work there is an advantage in oil immersion, as it facilitates temperature measurement and therefore correction of values for coefficient.

Below 10 ohms, shunts should be of the four-terminal type. With a low resistance it is essential to define the current and potential points. The current terminals must be sufficiently massive to carry appropriate leads for the maximum current. The potential points must be located where no change in the voltage-drop can be effected by different clamping of the current leads. Fig. 17 shows a shunt constructed for 30 000 amperes with a voltage-drop of 75 mV. The current terminals in this case are large copper laminations. The potential points are located upon the massive shoulders of the casting.

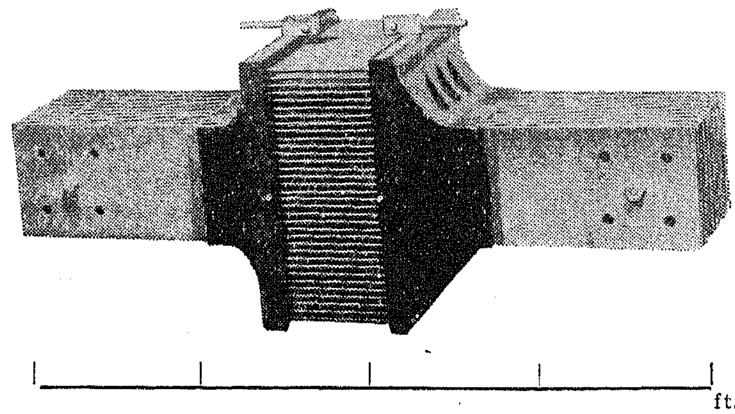

Fig. 17

These shoulders extend well beyond the resistance element, and thus form a complete ring of very solid metal outside the flow of the current. The result is that the surface then becomes an equipotential surface with almost any distribution of current to the shunt. With complete dissymmetry of current flow, the maximum change in potential distribution on the shoulders where the potential points were situated did not exceed $0 \cdot 6\ \%$. The dissymmetry will never be more than a small fraction of this when the resistor is in use. The apparent change of resistance with different current-distributions is the biggest problem in the economical design of such large shunts. In smaller shunts it becomes proportionately easier. It may be noted as a matter of interest that the resistance value of a four-terminal shunt used for potentiometry is really the mutual resistance between the current terminals and the potential terminals, i.e. the ratio of the voltage-drop at the latter to the current flowing in the former. The same value of mutual resistance should be found if the current is fed into the potential terminal and the voltage-drop measured at the current terminal, i.e. the circuit should be symmetrical.

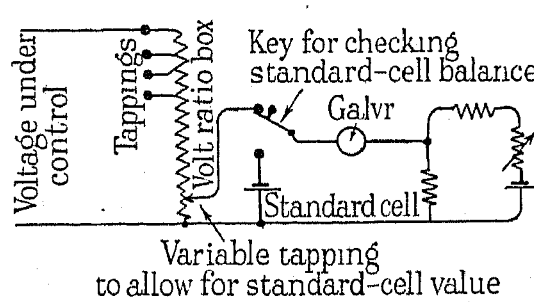

Fig. 18

Wires dissipate heat much more efficiently than sheets and are therefore more economical as regards material.

For voltage measurements higher than the range of the potentiometer a voltage-ratio box is connected across the voltage to be measured. In its simplest form this device consists of two resistance coils in series, one being a suitable fraction of the whole so that the voltage-drop thereon is some simple fraction of the whole.

If the resistance of the voltage-ratio box is too high

there will be a considerable loss of sensitivity in the measurement. On the other hand, a low-resistance voltage-ratio box means a large power dissipation in the resistance and consequently greater bulk and cost, or greater errors due to temperature-rise.

For measuring voltages at fixed values, as in meter calibration, instead of the voltage-ratio box a voltage-standardizer can be used (see Fig. 18). This is a special type of potentiometer for balancing the voltage-drop of the voltage-ratio box against the standard cell. To avoid excessive use of the standard cell, when the instrument is in continual use a subsidiary circuit is used to hold the balance, and the subsidiary circuit is adjusted from time to time against the standard cell. If reasonably large accumulators are used for the potentiometer, the current will remain steady to a few parts in a hundred thousand after a few hours. For this reason it is best to keep the battery always connected to the potentiometer.

The resistance of the potential circuit, including the galvanometer, potentiometer, and external circuit, limits the sensitivity. It is a mistake to suppose that the most sensitive moving-coil galvanometer will be one equal in resistance to the circuit to which it is connected. This is the condition of maximum power for a given voltage, but that is not the practical condition of maximum sensitivity. The reason is that, to be of practical use, a galvanometer should be approximately critically damped. The external circuit damps the galvanometer. The sensitivity depends upon the field strength of the galvanometer magnet, but so does the damping. High field-strength means high damping resistance. On a circuit equal in resistance to the galvanometer the field strength of the magnet would have to be so reduced to prevent over-damping that the sensitivity would be lower than if a low-resistance galvanometer with a strong field were used.

The most sensitive condition for any potentiometer circuit is a galvanometer with the lowest possible resistance and highest possible field strength that gives critical damping or slight over-damping. In practice, therefore, a magnetic shunt should be provided with the galvanometer to suit various circuit conditions. If no magnetic shunt is available the galvanometer resistance should be not more than one-third the circuit resistance, as this gives a very good all-round compromise.

In measurements on circuits where high voltages exist, the potentiometer should always be arranged to be at earth potential. If a shunt is used for current measurement it should be on the earth side; so too should the tapping of the voltage-ratio box. Fig. 19 indicates what this implies. Tests should never be so arranged that large voltage-differences exist between different test circuits brought to the potentiometer, otherwise considerable errors may occur due to leakage currents. No damage can be done to the potentiometer if the above precaution is observed. The use of fuses as a protection against wrong connections is not very satisfactory, because fuses which blow at very small currents are always sources of thermo-electric effects. Very fine copper fuses avoid this, but are often troublesome as they are liable to accidental breakage and corrosion.

Old instruments are particularly liable to leakage and polarization troubles. When ebonite has been exposed to sunlight a chemically active film may cover its surface and cause leakage between the battery terminals and galvanometer terminals and also electrolytic polarization between different parts of the instrument, resulting in unsteady readings and considerable inaccuracies in the case of measurements of high-resistance circuits. The ebonite can usually be cleaned with water to remove the acid, and finally dried with turpentine. In some work, rubber-covered leads have been the source of strong electrolytic action, where chemical contamination was taking place. Bare wire on clean insulators is safer in such conditions.

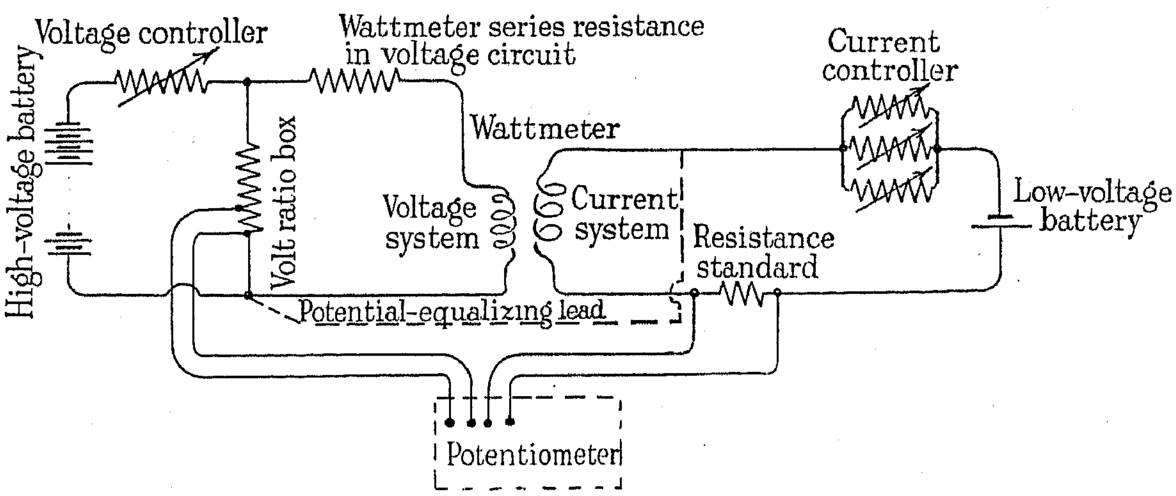

Fig. 19

Among the measurements for which the potentiometer is uniquely suitable may be mentioned the following:—

Calibration of voltmeters, ammeters, and wattmeters.

Measurement of temperatures by thermocouples.

Measurement of resistance of copper cables by comparison with standard.

Inter-comparison of resistance standards.

Measurement of earth resistivity.

Photometry: photocells and standardization of filament lamps.

Determinations of *pH* values.

[The discussion on this paper will be found on page 524.]

DISCUSSION BEFORE THE METER AND INSTRUMENT SECTION, 3RD MARCH, 1939

Dr. E. H. Rayner: The potentiometer is a fundamental electrical instrument, and any constitutional or accidental errors to which it may be subject at once become reflected in technical developments and measurements of all kinds in factories, and also in the charges for electricity to the public and in the financial results of our operating companies. For that reason, the Electricity Commissioners have assumed control of the quality of potentiometers and other fundamental apparatus necessary in meter testing stations. The potentiometer is not a very old instrument, but the idea seems to have been thought of 90 years ago. When I was young it took the form of two resistors put in series; in use, a plug was taken out of one box and put into the other. I was given to understand that that apparatus was suggested by Poggendorf. Was this actually the case, or was this type of potentiometer Rayleigh's idea, as is suggested in this paper?

The potentiometer is really only a balancing machine, and it is important that the accuracy of the apparatus of a standardizing character with which it is used should be about the same as that of the potentiometer. Some of the apparatus used with the potentiometer has not always had as much expert attention and supervision as has been given to the potentiometer itself, particularly as regards resistors for large currents. I have no doubt that that has been largely due to the difficulty of obtaining large currents, and of keeping them steady. It is in this respect that the potentiometer method fails as compared with bridge methods.

In the further remarks that I have to make, I have been helped very considerably by my colleague, Mr. Leaver, of the National Physical Laboratory, who has had much experience in testing apparatus of this kind.

Slide-wire contacts (mentioned on page 516 of the paper) should be free from the wire except when contact is desired. Also, the pressure should not be under the control of the operator. These important factors have not always received attention. As regards the scheme shown in Fig. 5, two advantages arise from the necessity of shunting the slide-wire: first, a true zero; and secondly, the possibility of measuring negative values.

Turning to the question of resistance materials for potentiometers, manganin is naturally used practically always. I have never been quite convinced, however, that it would not be worth while to make potentiometers and other high-class apparatus completely of copper-nickel alloy, such as eureka. The copper-nickel alloy might be continued right up to the galvanometer. Such a scheme would avoid the hundreds of joints between dissimilar metals which exist with the usual apparatus. There would be no such joints inside the potentiometer, and the two or four needed outside could be kept at a constant temperature. I should like to know whether this idea has been tried out in practice. One advantage of copper-nickel alloys is that they have a resistivity/temperature relation which is almost linear. The disadvantage is, however, that copper-nickel alloys give with copper a thermal e.m.f. equal to about 20 times that resulting from manganin under the same conditions. But copper-nickel alloys have the great advantage that they can be soft-soldered.

To ensure the satisfactory working of a potentiometer from day to day, the current should be kept on day and night, and it may be found desirable to keep the battery at a constant temperature. In my opinion, the accumulator should last for about a fortnight without having to be recharged. Two accumulators may be used, and charged in consecutive weeks. When they have been charged, they may be connected for a day or so to a dummy load before being put on to the potentiometer.

A difficulty in the design of resistors for the measurement of large currents, 1 000 to 20 000 amperes, is to ensure that the voltage drop is independent of the method of connecting the resistor to the outside circuit. When the resistor has a number of bolt holes or studs for the connection of a number of conductors in parallel, uneven distribution of current among them frequently affects the effective resistance appreciably. One method of improvement is to make the end connections sufficiently long and to arrange a constriction between the part where the connections are made and the part to which the resistance metal is fixed. Sufficient metal must be left at the constriction to carry the current, but the neck can be very short. A saw-cut will often be found very effective.

The voltage-standardizer scheme shown in Fig. 18 differs only in respect of the little subsidiary battery on the right from one which we have used for many years*—ever since we undertook precision measurements of a.c. voltages—for establishing the proper current and voltage distribution in a potential divider up to about 260 volts.

I see that the author has indicated an incorrect method of connection in Fig. 19;† which has sometimes given rise to small errors which are difficult to locate. He shows a potential-equalizing lead which at the right-hand end is connected to the circuit between the resistance standard and the current circuit of the wattmeter, the idea being to ensure a negligibly small voltage between the voltage and current windings of the wattmeter. If the use of this equalizing lead brings the circuits at the two ends to the same potential, which would not be the case without it, current must flow in it, and the currents in the wattmeter and in the resistance standard will differ by the amount of this current. To avoid this error the equalizing lead may be connected to the other end of the wattmeter coil, between the wattmeter and the current controller.

There is always a risk of appreciable current when such a lead connects networks with different sources of supply. Neither the high-voltage battery nor the low-voltage battery, with their acid surfaces, switchboard connections, and control apparatus, can be expected to be really insulated from earth; and the natural voltage of a 2-volt cell, if it is part of a battery consisting of a number of cells in series, may be several volts above earth potential.

I should like to emphasize the importance of keeping as low as practicable the resistance of the connecting conductors between the potential points on resistance elements and the potential terminals. These conductors are sometimes several inches in length and made of

* See *Journal I.E.E.*, 1913, vol. 51, p. 313.

† Corrected for the *Journal*.

quite thin wire. The additional resistance resulting from this kind of design renders their verification by bridge methods troublesome and reduces unnecessarily the technical value of the apparatus.

Mr. W. Phillips: The potentiometer that is in most general use is the one which we know as the slide-wire potentiometer, and which is shown in Fig. 3. Given a suitable design this form of potentiometer may provide a high degree of subdivision. It is simply a matter of what one is prepared to pay for such a piece of apparatus. For instance, I have in mind a potentiometer of the slide-wire type where the slide-wire is itself 3 in. in length and connected in series with 149 loops of wire; the scale of the slide-wire is about 6 in. long, divided into 200 divisions, and the full range of the potentiometer is 1·5 volts. Thus each division on the slide wire is equivalent to 1/30 000th, measuring down to 0·00005 volt; and that again can be subdivided by eye, if necessary. Such a high degree of subdivision is quite unnecessary for ordinary voltmeter and ammeter measurement. Another form of potentiometer with a slide is used for measuring down to 0·0002 volt. This potentiometer has a slide-wire in series with 29 coils. Quite a number of these potentiometers are now in use for meter testing.

In the form of potentiometer which I have just mentioned as having 29 coils and a slide-wire, the circuit for checking the standard-cell balance is arranged in series with the potentiometer circuit itself, and not in parallel, as in the instance mentioned by the author. It requires double the volts in the battery, but uses about half the current. The potentiometer has a plug-switch arrangement for reducing the range to 1/10th, and the standard cell can be checked without disturbing the potentiometer setting when using either range.

Measurements by the potentiometer are capable of a very high degree of sensitivity. In making tests of current and voltage and in checking instruments, one should not forget that the absolute accuracy of measurements depends as much on the accessories which are used with the potentiometer as upon the accuracy of the potentiometer itself; this is especially important when one is using standard resistances, particularly those of the air-cooled pattern. If these resistances are mounted in a test room and boxed so that they are without free air circulation, a temperature-rise of 20 or 30 deg. F. may occur, which can lead to an error of 0·03 % or more.

In heavy-current shunts such as those shown in Fig. 18 I have used the types of terminal that Dr. Rayner described. We generally select the strip on the basis of its temperature coefficient, and in certain cases we compensate this by appropriate methods.

Mr. A. Felton: The direct-current potentiometer is now the fundamental standard for the calibration of indicating instruments in testing stations of supply authorities, and is therefore of more interest to meter engineers at the present time than it has been in the past.

The calibration of indicating instruments, particularly wattmeters, involves careful consideration of the testing circuits if errors are to be avoided.

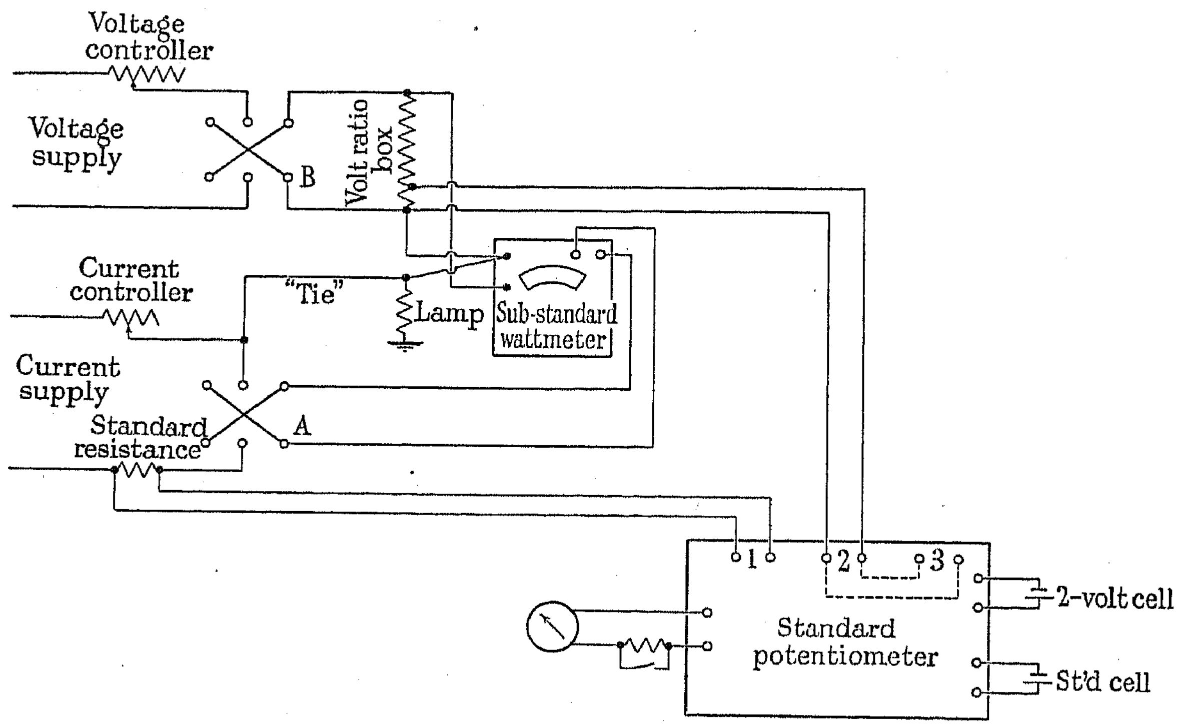

Fig. A

The author has specified two conditions for the accurate use of a potentiometer: (1) The potentiometer should always be at earth potential. (2) Tests should never be arranged so that large voltage-differences exist between different test circuits brought to the potentiometer.

The circuit shown in Fig. 19 complies with these conditions, but unfortunately it is incomplete in that the reversing switches which are essential in the calibration of a wattmeter are omitted. The position of these reversing switches must be carefully considered.

The best practical circuit appears to be that shown in Fig. A. In this circuit the potentiometer is maintained at earth potential during all measurements, while the potential leads from the current standard and from the voltage-dividing resistor are substantially at the same voltage. The disadvantage lies in the fact that in one position of the reversing switch B the voltage applied to the potentiometer from the volt-ratio box is in the wrong direction and the potentiometer will not balance. It is therefore necessary to cross-connect the potentiometer circuits 2 and 3 as shown. In either position of the

reversing switches A and B the current through the wattmeter is measured on Circuit 1 of the potentiometer, while the voltage on the wattmeter is measured on either Circuit 2 or Circuit 3, according to the position of the reversing switch (B).

Mr. O. Howarth: The vernier potentiometer shown in Fig. 10 embodies no provision for getting an exact zero on the potentiometer, because the zero-position on the vernier dial does not represent an equivalent potential to that indicated by the zero-position on the third dial. Is it not possible, by an extension of the method shown in Fig. 5, to get the correct zero?

Dealing with the use of the potentiometer, and Mr. Felton's diagram (Fig. A), it seems to me that the best way of getting over the difficulty associated with a voltage standardizer is not to earth the system at all, but to rely upon the insulation. In view of the risk of inaccuracies creeping in, it appears that voltage standardizers and voltmeters used in this manner are very undesirable.

I should like to ask how the performance of a precision potentiometer would be affected by arranging for oil immersion of the resistance units, and possibly also of the switches. Also, at what intervals does the author consider that the contacts on a potentiometer should be cleaned? I am thinking of a potentiometer used in a reasonably clean atmosphere and kept at a reasonably constant temperature. The cleaning must, of course, be done under skilled supervision. Would the author recommend cleaning with ordinary paraffin, or pure paraffin; and, if not, what would he recommend?

Is there likely to be any trouble where the slide-wire of a potentiometer is laid on slate? Does this practice cause gradual corrosion?

Is there any objection to using an ordinary universal shunt to vary the galvanometer sensitivity?

I should like to emphasize the necessity of employing highly skilled personnel to operate potentiometers if accuracy is to be ensured.

Mr. W. L. Beck: I cannot quite agree with the author's statement on page 518 that a slide-wire is not to be recommended for the final dial of a precision potentiometer. A well-designed manganin slide-wire, suitably enclosed and lubricated, will give satisfactory service for long periods without attention, and it cannot be denied that a slide-wire of similar dimensions to the 100-point switch will give from 5 to 10 times the degree of subdivision. With regard to life, I have a potentiometer of this type which has been in continuous use for at least 10 years, and is still using the original slide-wire. When it was checked recently, its accuracy was found to be within 1 part in 1 000 of its original calibration, in spite of the fact that the contact must have travelled over the wire at least 50 000 times.

Apart from the brief reference on page 521 to the Callendar recorder, the author does not mention the automatically balanced potentiometers which are used extensively for recording and controlling the temperature of furnaces. These potentiometers have undergone considerable development since the original Callendar design was evolved, and now generally employ motor drive and a simple robust mechanical device which moves the slide-wire contact to the balance point without introducing any control on the galvanometer. The recording pen and control switch are coupled to the moving contact mechanically. At suitable intervals, a switch in the galvanometer circuit is operated and a gear changed so that the potentiometer automatically standardizes its working current against a standard cell.

Mr. H. Parry: It seems to me that all standard cells should have a high resistance in series with them. Otherwise it is possible to lower the voltage of the standard cell by as much as 1 % by keeping the key pressed for a considerable period.

My experience shows that it is possible to get errors of as much as 1 % with low-resistance vernier dials, and unless a cross-check can be made one has no idea that those errors exist.

In tests where the voltage has to be reversed, such as in checking wattmeters, unless great care is taken it is possible to get a wandering zero on the galvanometer, with change of potential.

I should like to know what is the stability of the zero of the circuit shown in Fig. 11. The resistance of the vernier dial may alter slightly and thereby upset the zero.

Mr. L. B. S. Golds: The author states that the contact resistance of the vernier dial switch precludes the use of a multiplicity of vernier dials. Therefore, the voltage drop due to the contacts of the potentiometer must affect the voltage drop in the vernier dial. This is the only disadvantage in what is otherwise a most useful type of potentiometer for general instrument calibration.

I appreciate that by making the total resistance of the vernier dial high it is possible to reduce the effect of the contact resistance, but, on the other hand, the total resistance cannot be increased without loss of sensitivity. I should therefore be glad if the author would give a method of checking this switch for contact variations. I would suggest that it would be an advantage for checking if the ends of the vernier dials were brought out to a pair of terminals.

Mr. E. S. Ritter: With regard to Fig. 9A, the one form in which I have seen this used is with a 1 000-ohm resistor connected between the point marked "0" on the main dial and the left-hand terminal. The instrument is sometimes mistaken for a resistance box, and it is wrongly supposed that the resistances from the "0" to the contact of the slide-wire at the bottom and from the slide-wire at the bottom to the top add up to the reading that one gets of the percentage of the 1 000 ohms as a rheostat.

Mr. R. Mines: On the micrometer, a ratio of 1 000 : 1 is divided into 25 : 1 and 40 : 1. Using dials with alternately 25 and 40 coils would afford a reduction in the number of dials required, without the number of coils on a dial rising to such a high figure as 100.

Mr. S. Hunt: In view of what has been said by previous speakers regarding the introduction of parasitic voltages in wattmeter standardizing by means of the potentiometer, I should like to know why we cannot use standard 12-in. voltmeters and ammeters (which can be so easily checked separately on the d.c. potentiometer) for wattmeter checking. This method would require only one skilled operator, and would avoid bringing mixed circuits to the potentiometer, which means several operators crowded together to do the necessary controlling and watching of the current and voltage circuits.

When using a potentiometer to check a reading of 400 volts on my 12-in. voltmeter, I find that a variation of some 20 to 30 millivolts' movement on the spot galvanometer causes no movement of the pointer; so that I feel that for wattmeter testing the potentiometer will give no greater accuracy than the method I have suggested, while it will have all the possibilities of error which have been outlined by the author and the previous speakers.

Mr. H. W. Hockley: An important factor in the production of potentiometers is the adequate ageing of the various coils and the slide-wire (if one is used) which form the potentiometer circuit. Generally speaking, a coil must be aged for some months before it can be said to have settled down to a consistent condition; and even after that, when the coils have been mounted and connected up, a further ageing period must take place before the final calibration can be effected. Does the author know of any satisfactory artificial ageing process which can be used as an alternative to the rather long natural ageing process which is now necessary?

With regard to what is said on page 522 as to shunts, has the author found any difficulty in making satisfactory mechanical and electrical joints between the wires and the shunt ends? In using sheet manganin for precision shunts, it has been found necessary to hard-solder the material into copper strips before soft-soldering the units so formed into shunt ends. Has it been found necessary to use similar methods to make satisfactory joints between the manganin wire and the shunt ends?

Mr. W. H. Eastland: There recently came to my notice a shunt with a manganin resistance element that had been soft-soldered to the shunt ends and had been used in conjunction with a watt-hour meter of 8 000 amperes' rating. After 2–3 years' service the joints had become defective, and this had affected the accuracy of the watt-hour meter to the extent of about 7 % or 8 %. It is usually easier from the manufacturing point of view (and much cheaper) to soft-solder heavy-current shunts, but from the electrical point of view it is necessary that the shunts should be hard-soldered.

Dr. L. G. A. Sims: I should be glad if the author could give a little more information about modern slider design, particularly with regard to the treatment one should apply to slide-wires to make sure that the contact remains satisfactory over a fairly considerable period of time. Is there any appreciable difference between the behaviour of the slider when in use on a d.c potentiometer, as compared with its use on an a.c. potentiometer?

Mr. H. W. Leaver (*communicated*): Dr. Rayner has made reference to the large number of potentiometers I have had the opportunity of examining, and I wish to make a few remarks regarding the testing of these instruments and their accessories.

The most convenient method which has been found for testing potentiometers of the slide-wire type, and those having a degree of subdivision not finer than 1 part in 10^4, is direct comparison with a calibrated potentiometer of the vernier type, having a subdivision of 1 part in 10^5. The errors present in such a standard potentiometer would rarely exceed one step on the last dial, and the errors in the results of such a comparison would be less than the possible error in setting the slide-wire index of an instrument under test. In the case of potentiometers having a degree of subdivision finer than 1 part in 10^4, it is important to find means of determining the equality of the individual coils. If the contact studs are accessible, special clips may be used to make connection with adjacent pairs of studs. One manufacturer provides special testing terminals which allow of connection being made to individual coils and to the slide-wire. This enables the resistance of each coil, and that of an equivalent length of the slide-wire, to be determined in terms of the resistance of, for instance, the first coil on the dial. It is only necessary to determine relative values of resistance, and the measurements can be made by means of a second potentiometer, or a simple auxiliary potentiometer circuit consisting of a few standard resistance coils in series with a finely adjustable rheostat. In the latter method, the magnitude of any inequality, which will usually be small, can be observed by galvanometer deflection.

Should it be found impossible to make temporary test connections, it becomes necessary either to compare the successive steps on a dial with a series of standard resistance coils used in an auxiliary potentiometer circuit, or to adopt the method described on page 519 of the paper. These methods are, however, laborious compared with those previously mentioned.

Resistance standards for current measurement are constructed with capacities ranging from a fraction of an ampere to several thousands of amperes. Since large currents are difficult to maintain at steady values, potentiometric methods are often inconvenient and bridge methods become more suitable. The potential leads of the resistance standard then form portions of the bridge arms, and allowance has to be made for their resistance. It would be advantageous if the resistance of these leads were kept low, say, of the order of 0·001 ohm.

Bridge methods are also used in testing voltage-dividing resistances, and here again it is of advantage if the internal leads are of low resistance, especially those used in the circuit of the "potentiometer" section. Their resistance should be negligible in comparison with that of the section to which they are connected.

It will be gathered from the foregoing remarks that there are details in the design of potentiometric equipment which, if given more attention, would materially facilitate the adjustment of equipment in course of construction and the testing of the finished apparatus.

Mr. D. C. Gall (*in reply*): In reply to Dr. Rayner, a summary of the history of the potentiometer is given in Chapter 14 of my book, "Direct and Alternating Current Potentiometer Measurements." Mr. D. Rutenberg has now published the full account in the *Annals of Science* (vol. 4, April, 1939).

The original conception of the potentiometer method was due to Poggendoff and was published in 1841, but the circuit used by him was not the one to which Dr. Rayner refers. That would appear to be due to Lord Rayleigh, and was used by him in 1885 in investigations on the Clark cell.

With regard to the use of the copper-nickel alloy throughout the construction of the potentiometer, this is a very interesting point and it would undoubtedly remove some of the thermo-electric effects, but it would appear to offer a good many practical objections in respect of the

manufacture of an industrial instrument. Copper-nickel is not easy to work and, as it is a high-resistance alloy, the switch contact resistances would be high. We have manufactured a number of switches of this material for use in thermocouple circuits, but their performance as switches is not so good as with the low-resistance materials normally employed. There are, moreover, differences in thermo-electric effects between different batches of the alloy, and as soldered joints in the coils and wiring are almost inevitable it would be difficult to carry out the idea in an ideal manner.

With regard to the temperature coefficient, this is not usually a very troublesome matter in a precision potentiometer because the same specimen of resistance wire is used throughout the construction, so that the ratios which exist between the resistances remain constant independently of the temperature.

With regard to the design of large-current shunts, I should like to record the great debt I owe to Dr. Rayner for the frequent advice and help he has given in the construction of these units. The form of construction which we employ is based very largely upon the N.P.L. design. In my experience the degree of perfection is really a matter of economics, and, in practice, a compromise which gives the desired accuracy under normal conditions of use has to be accepted in the case of very large shunts for industrial use. Although, by abnormal connections, it may be possible to disturb the current flow, and so affect the voltage drop, it may be reasonably expected that under normal conditions of use the current flow will be sufficiently uniform to maintain the initial accuracy.

I am very grateful to Dr. Rayner for pointing out an incorrect connection in Fig. 19; I have taken the opportunity of rectifying this for the *Journal*.

The two-dial arrangements which Mr. Phillips mentions are undoubtedly good combinations and capable of giving a high degree of accurate subdivision with a very simple type of circuit. The single dial with the large number of studs is certainly quicker in use than two dials having the same equivalent degree of subdivision, but there is a practical limit to this method and even with 150 studs the dials tend to become rather large and it may be more economical to rearrange the circuit.

With regard to the relative merits of the series circuit and the parallel circuit for independent standardization of the potentiometer, for many years we used the series circuit but we have now abandoned it for the parallel circuit as the latter is, in my experience, more easily checked—it really forms a simple bridge circuit of which the equivalent points can be compared with the greatest ease. The standard-cell circuit, in parallel with the main potentiometer circuit, is of higher resistance, so that the potentiometer does not take twice the current. One of the great advantages of having a potentiometer with a very long range, and of high precision over the whole range, is that it extends the usefulness. There may be no need to measure to five figures at 1 volt, but when measuring much lower voltages the available figures may be very valuable and enable accurate calibrations to be carried out over a much wider range.

Mr. Felton raises several points of very great importance in connection with meter testing. My own conviction in the matter is that the reversals should be made at the coils of the instrument under test, and not externally; that is to say, a precision wattmeter should be provided with a switch or other means of reversing both the voltage coil and the current coil on the instrument itself. If this is available there is no need for all the complications of reversing the main batteries and the potentiometer connections, and it would seem that there should be no difficulty in making this modification to existing instruments if its importance is appreciated. It is for this reason that we have always kept the series resistance of the voltage system external to the wattmeter which we make. It is a simple matter to change this over in order to check the effects of reversals. If the circuit arrangements become such that the potentiometer requires reversal there will be no difficulty in arranging for reversing switches on the instrument to do this. The same would apply when a voltage standardizer was used. It would be a simple matter to make a ganged switch to carry out the reversal of the battery and standard cell in one movement.

In reply to Mr. Howarth, the zero of the vernier potentiometer circuit shown in Fig. 10 is, in practice, about 1/10 of the least count on the lowest dial. This is inevitable in the simple vernier type of circuit used, as shown, but is much reduced by the series-coil type of vernier dial and by the cross-connection of the two zeros on the main and the third dial. It is not possible to make a cross-connection to the zero of the vernier dial, because this moves about. Neither is it possible to connect the zero of the third dial to a point intermediate between " 0 " and " 1 " on the main dial, because sometimes this section would be shunted by the vernier dial and sometimes not, and therefore the potential of this tapping point would alter. The only satisfactory method of which I am aware, of obtaining a true zero to the vernier circuit, is that shown in Fig. 11, and it is gratifying to learn that this device has now been adopted by other instrument makers.

With regard to the oil-immersion of precision potentiometers, in my experience oil-immersion is not very satisfactory unless the oil can be kept continuously dry. One method of doing this is to bubble specially dried air through the oil, but this must be done continuously otherwise the oil absorbs moisture from the atmosphere and attacks the resistance coils. It was the practice of my company, at one time, to keep all standard resistance coils in oil, but when these were examined it was found that they were saturated with water which appeared to have been extracted from the oil by osmosis through the insulation. The coils were badly corroded, and all had to be scrapped. For general potentiometer work of high precision there does not seem to be any need for oil-immersion. The temperature inside a substantial wooden case remains very constant, and the substantial aluminium panel which is fitted over the dials maintains a very uniform temperature on the switch panel. Thermo-electric effects are generally external to a well-designed potentiometer, and are therefore unaffected by oil-immersion.

With regard to the cleaning of potentiometers, this depends very largely upon local conditions. There are many potentiometers which have not been cleaned for 10 years and which are still functioning well. In other

situations cleaning is necessary every month. As a general rule, potentiometers should be cleaned every 3 months. The cleaning is a very simple matter—it is only necessary to remove the cover and squirt a little solvent on to the contacts to remove old dirt and grease, and after wiping off the dirty solvent to apply a little medicinal paraffin to provide lubrication. On no account should any abrasive be used on the contacts, as this charges the surfaces and continues to cut the contacts for years and the contact resistance is thereby increased. In the production of the potentiometer contacts no abrasive is used.

With regard to slide-wires wound on slate, in my experience this gives no trouble if the slate is properly treated. Slate is a porous material but can be impregnated with bakelite and baked so that it becomes impermeable to moisture. The objection to using an ordinary universal shunt in the galvanometer is that the external resistance is low when the galvanometer sensitivity is reduced, and this has caused more than one potentiometer to be accidentally burnt out when measuring low-resistance circuits. With a large out-of-balance voltage in a low-resistance circuit, if the galvanometer is short-circuited a large current can pass round the potentiometer. If a series resistance is used in the galvanometer to reduce the sensitivity this cannot take place, and the instrument is thoroughly protected during the preliminary stages of obtaining balance. This is the reason for advocating the use of a series resistance instead of a universal shunt.

In reply to Mr. Beck, as a convenient means of continuous subdivision there is nothing to take the place of a slide-wire. The travelling contact has always been a weakness, in my experience, although it becomes economically essential in instruments where the degree of absolute accuracy need not be very high. It is true that a slide-wire can give 5 to 10 times the degree of subdivision of a 100-point switch of similar diameter, and is therefore equivalent to an additional dial, but each point on the 100-position switch will be a very much more accurate potential point than that to which it is possible to set the slider. Although the overall accuracy of the slide-wire at its maximum setting might be such that it would be possible to read to 0·1 %, it will be obvious that at the lowest setting it could be read to no degree of accuracy at all, whereas in the case of a set of stud points the error of every step need not exceed 0·01 % of the total. The stud dial is therefore essentially a more precise method of subdivision than the slide-wire, but often less convenient and in some cases quite unsuitable, as in the case of the recording instruments mentioned by Mr. Beck. For some years we used plated manganin slide-wires, but found them less satisfactory than platinum-silver. Bare manganin oxidizes very rapidly.

In reply to Mr. Parry, it is very easy temporarily to lower the voltage of a standard cell by taking current from it; a large series resistance in the standard-cell circuit is a protection, but this must be very large to be really adequate. The resistance of most standard cells is of the order of 1 000 ohms. It will be easy to see that a current of only 1 microampere will lower the terminal voltage by 1 millivolt. For this reason a sensitive galvanometer and a large series resistance is preferable to a very low-resistance standard cell and a less sensitive galvanometer. Low-resistance vernier dials often showed considerable errors in some of the older instruments where the contact resistance varied. The use of the high-resistance vernier dial in conjunction with the "Dual" contact switch has practically eliminated this source of error. The simplest check is of the zero: if the contact resistance of the vernier dial is bad the zero will have altered, and the possibility of this easy check is one of the advantages of having a true zero on the potentiometer.

With regard to the stability of zero in the instrument shown in Fig. 11, the electrical stability of the circuit is better than 0·1 microvolt. It is, however, a very difficult matter to measure these quantities unless great care is taken with the galvanometer circuit to avoid thermo-electric effects, due to external temperature-changes. In the older instruments where no panel protected the switches the heat of the hand would produce quite appreciable instability, of the order of several microvolts. The final tests of precision potentiometers must be made with the instruments in their cases and with the panels covering the contacts and after the instrument has had ample time to reach temperature equilibrium. These effects are usually below the 10-microvolt level, so that such rigid precautions are not necessary for the measurements not involving these small values.

In reply to Mr. Golds, variations in the contact resistance of the vernier dial are the limiting factor in its use. In practice, with the "Dual" contacts now used this resistance does not vary more than a few microhms. It is easy to show that the effect of this variation of the circuit employed is considerably less than the least count of the potentiometer. The simplest method of checking this point is to check the zero. If the contact resistance of the switch is increased, the zero voltage will have increased. It would be a simple matter to bring out a terminal from each end of the vernier dial to enable a check test to be made of the contact resistance by simply connecting the galvanometer across the contact. Any variation in the deflection would indicate a variation in contact resistance.

I have seen a student make the mistake to which Mr. Ritter refers. I think this can be avoided by more adequate and descriptive engraving on the instrument.

In reply to Mr. Mines, occasionally instruments are made with non-decade units of subdivision, but, in general, they are much less convenient to use and direct-reading dials are less likely to cause mistakes. I prefer, as a general principle, that an instrument should indicate directly what it measures, without any odd multiplying factors. The 100-stud dial does not offer any practical difficulties in manufacture.

In reply to Mr. Hunt, I think the order of the errors in the potentiometer which have been demonstrated and discussed would be very much less than those to be found in a 12-in. voltmeter, so that the potentiometer is essentially the more accurate instrument.

In reply to Mr. Hockley, so far as I am aware there is no short cut to perfection, but a good deal can be done to relieve the internal strains in resistance coils so as to enable them to settle down quickly. The type of construction used in these precision potentiometers allows for most of the coils to be annealed in their final form at a

fairly high temperature, after which they are "pickled" and washed and lightly varnished to avoid corrosion. The coils which cannot be so treated are baked at the highest possible temperature before final assembly. All joints are hard-soldered, and the soft-soldering of resistance materials is never used for potentiometer coils. The manganin wires or sheets used for resistance standards are always hard-soldered into copper ends, and the copper ends soft-soldered to the terminal blocks. It is necessary to take care in the cleaning of the resistance material, in order to ensure a perfectly clean hard-soldered joint and not one which is just superficial.

In reply to Mr. Eastland, it has been often stated that certain classes of manganin could be soft-soldered, and many manganin-sheet shunts have been constructed on this plan. In my experience, however, it has never been satisfactory. Although the joints appear good, if they are cut open after a few years some sign of cracking in the joints is apparent. A great many ammeter shunts have been made in this way, but so far as ease of manufacture is concerned it is easier to hard-solder than to soft-solder manganin, because the soft solder does not flow freely. The hard solder flows in a beautifully clean joint, but a certain amount of judgment has to be used in settling the proportions of the end blocks. It is not easy to hard-solder a thin sheet or wire into a very massive block. Copper-nickel alloy soft-solders much more satisfactorily, but some time ago I met with a case where the soft-soldered joint burned-out in a shunt used for measuring very large short-circuit currents. Now all such joints are hard-soldered, to ensure low-resistance joints.

In reply to Dr. Sims, the essentials of a good sliding contact appear to be a non-corrodible surface and adequate pressure. If the pressure is too great, excessive wear takes place, but if it is too light the contact resistance is variable. It is our practice to fit a wiper to clean the wire when the sliding contact rotates. A small quantity of lubricant is also applied to the surface of the wire, but this may cause dust to adhere to the surface unless dust is rigidly excluded. The chief difficulty in the design is due to the small diameter of the wire usually required to obtain the necessary resistance. When this is mounted upon a cylinder only a small amount of surface is exposed. If wear takes place a groove is soon cut in the slider, of a depth equal to the exposed segment of the wire, and the contact is intermittently lifted. The material of which the slider can be made is usually limited by thermo-electric considerations. Our practice is to use a small-diameter wire for the sliding contact, so mounted that it can be easily replaced when worn, without disturbing the accuracy of the setting. Wear invariably takes place on the slider, and to an inappreciable extent on the wire. I have not noticed any appreciable difference between the sliders on d.c. potentiometers as compared with a.c. potentiometers, except that the vibration galvanometer is much more sensitive to intermittent jumping of the slider contact when it is rotated than a d.c. galvanometer. A vibration galvanometer is always used for testing the continuity of contact of sliders on slide-wires because of this effect. Sometimes a particular batch of wire will give intermittent contact, due, apparently, to ripples on its surface.

The method of testing potentiometers which is described by Mr. Leaver, is the method used in adjusting the coils during manufacture. A set of fingers for travelling round the dials is mounted in place of the switch during these tests. Such fingers are occasionally supplied to users of the potentiometers for their own particular purposes. In the case of a vernier dial it is not so straightforward to fit test terminals as in the simpler type of potentiometer circuit to which Mr. Leaver refers, where this is done.

With regard to the high resistance in the potential leads of four-terminal resistance standards, from the manufacturing point of view it is sometimes convenient to have such a resistance, as the adjustment can be made by moving the potential points along the resistance material. This probably accounts for this rather objectionable feature, but, in my opinion, this method of adjustment is unnecessary and the only occasion on which high-resistance potential leads are unavoidable is where thermo-electric compensated potential leads are used and part of the resistance material is employed to form the potential lead. By adopting this device it is possible to use materials other than manganin for the construction of precision potentiometer shunts.

FREQUENCY-CHANGING WITH MERCURY-ARC MUTATORS*

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SUMMARY

This paper deals with the existing systems for the conversion of 3-phase 50-cycle alternating current, to single-phase at $16\frac{2}{3}$ cycles, with mercury-arc mutators. Frequency-changing with mercury-arc mutators may be performed either with a direct-coupling mutator convertor or with a mutator convertor with intermediate direct voltage. The direct-coupling mutator convertor is characterized by the method of producing the single-phase voltage curve, which is built up from sections of individual 3-phase voltage curves; this method involves direct coupling of primary and secondary networks. The mutator convertor with intermediate direct voltage consists of a rectifier and an invertor having a d.c. circuit as intermediate element between the a.c. networks. No type of existing mutator convertor is perfect in itself. The future development of mutator convertors for traction purposes depends largely upon the demand for frequency-changing.

CONTENTS

(1) INTRODUCTION

The object of this paper is to give a report on the fundamentals of a method of frequency-changing which has been developed on the Continent and introduced by the German State Railways for practical experiments. Mercury-arc mutators are employed for the conversion of 3-phase 50-cycle alternating current to single-phase at $16\frac{2}{3}$ cycles, for traction purposes.

Frequency-changing with mercury-arc mutators may be performed in two different ways, either by direct conversion of the voltages with the direct-coupling mutator convertor, or by using an intermediate d.c. circuit with the mutator convertor with intermediate direct voltage.

(2) MUTATOR FREQUENCY-CONVERTORS

(a) Direct-Coupling Mutator Convertors

Basic circuit diagram and performance.

Fig. 1 shows the basic circuit diagram of the direct-coupling mutator convertor of the envelope curve type. The primary 3-phase system (a) supplies energy to the transformer (b). The star-point of the 6-phase transformer secondary winding is connected to one line of the secondary single-phase system (d). The free ends of the transformer secondary phases may be connected to the other line of the single-phase system (d) by way of two sets of single-anode, grid-controlled mercury-arc valves (c), one set of valves having their cathodes, and the other set of valves their anodes, connected to the single-phase system (d).‡

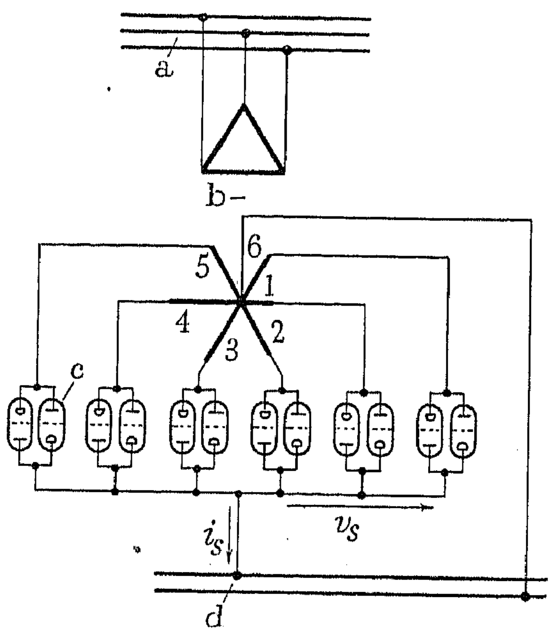

Fig. 1.—Basic circuit diagram of the mutator convertor of the envelope curve type.

a: Primary 3-phase network, 50 c./sec.
b: Mutator transformer.
c: Single-anode mercury-arc valves.
d: Secondary single-phase network, $16\frac{2}{3}$ c./sec.
1 . . . 6: Phases of the transformer secondary winding.
v_s: Secondary voltage.
i_s: Secondary current.

The operation of the mutator convertor and the formation of the secondary voltage may be understood with the aid of the schematic arrangement shown in Fig. 2, in which the valves shown in Fig. 1 have been substituted by a set of single-operated switches $S_1 \ldots S_6$.

In Fig. 2 switch S_1 is shown closed; the other switches are open. Switch S_1 connects the secondary transformer phase 1 to the single-phase system. The switch is closed for a given period only. When this period has elapsed switch S_2 is closed and switch S_1 is opened, thus replacing secondary transformer phase 1 by phase 2. After another period phase 3 is brought into operation by closing switch S_3 and opening switch S_2; and so on. The switches connect alternately each phase of the trans-

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‡ See Bibliography, (2).

former secondary to the single-phase system. The effect of this operation is illustrated in Fig. 3.

Fig. 3(a) gives the diagrams of the voltages v_1–v_6 of the transformer secondary phases 1–6, respectively. Fig. 3(b) indicates the closing periods of the switches S_1–S_6.

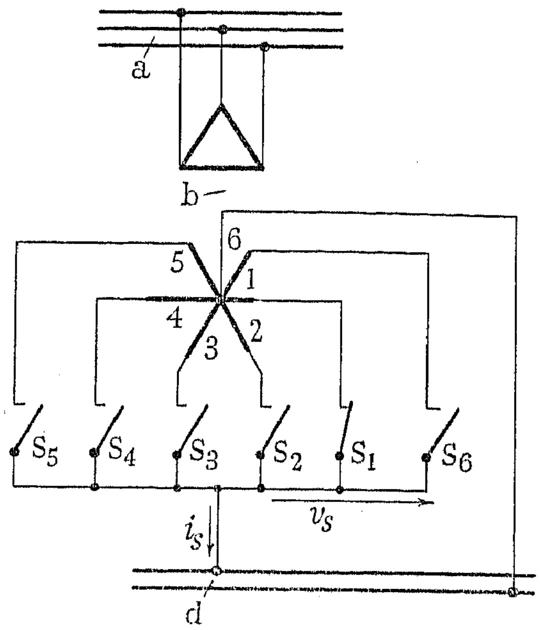

Fig. 2.—Schematic arrangement to explain operation of the mutator convertor (Fig. 1).

$S_1 \ldots S_6$: Single-operated switches.

Switch S_1, for example, is closed between t_1 and t_2, t_7 and t_8, t_{13} and t_{14}. Switch S_2 is closed from t_2 to t_3 and from t_8 to t_9; and so on. This results in sections of the voltages v_1–v_6 being cut out and joined to the heavy

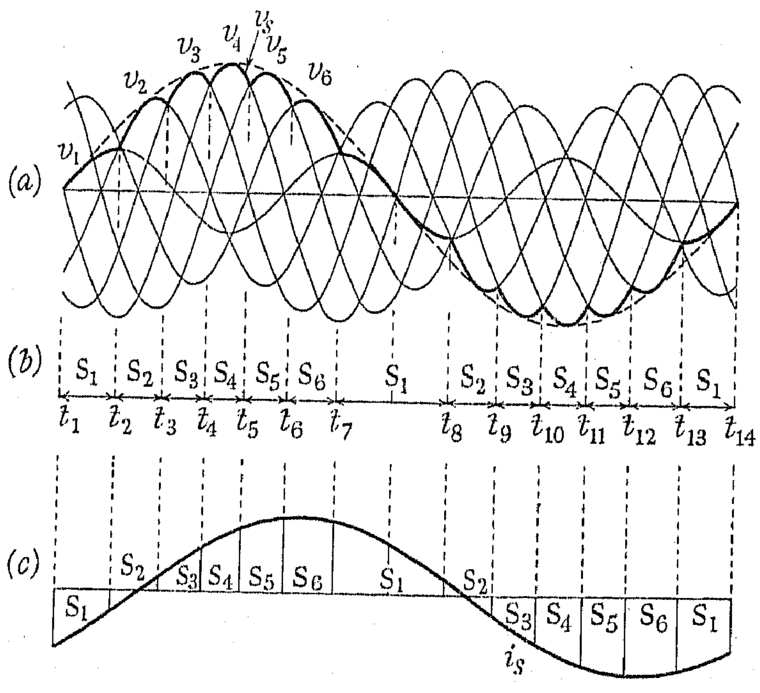

Fig. 3.—Formation of secondary voltage and current with the arrangement shown in Fig. 2.

(a) Formation of the secondary voltage.
(b) Closing periods of the switches.
(c) Conduction of the secondary current by the switches.
$v_1 \ldots v_6$: Voltages of the transformer secondary winding.

curve in Fig. 3(a), which represents the diagram of the secondary voltage v_s.

Fig. 3(a) shows that the frequency of the secondary voltage v_s is one-third of that of the primary voltages. The curve of v_s is made approximately sinusoidal by

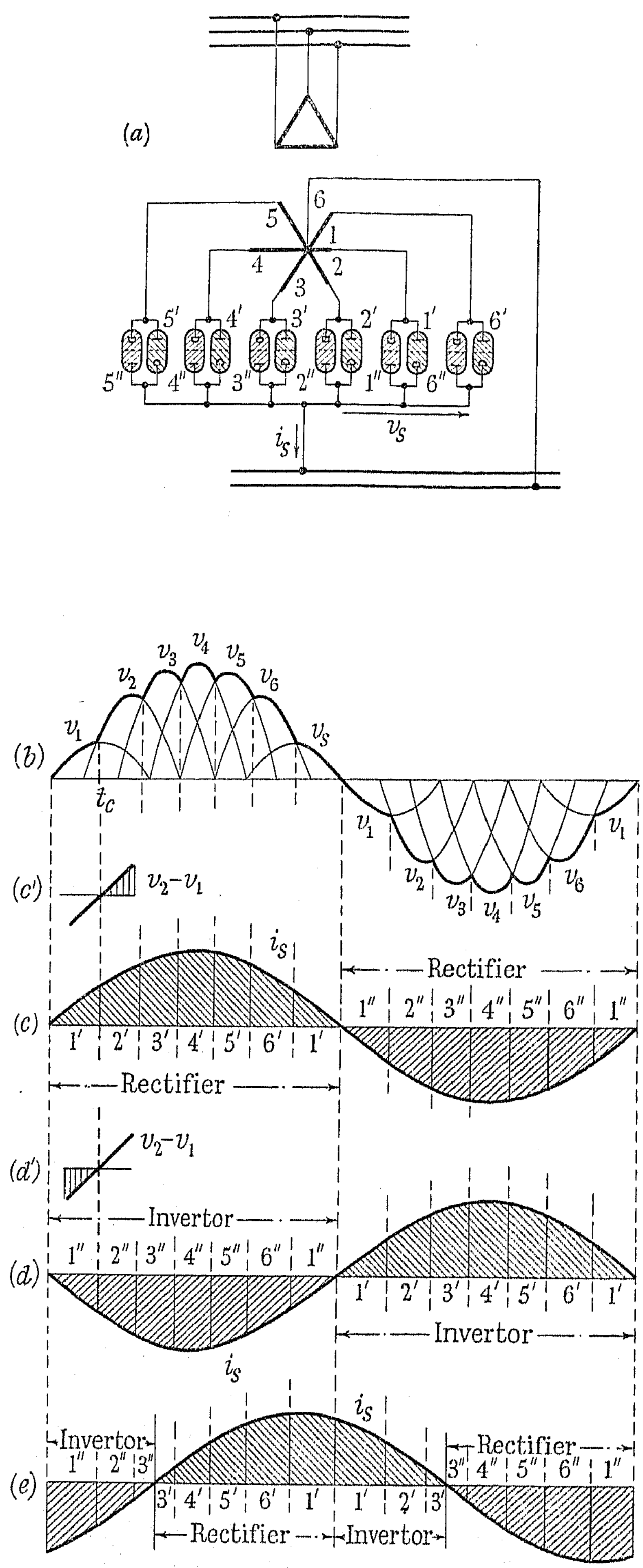

Fig. 4.—Flow of current through the mercury-arc valves of the mutator convertor Fig. 1.

(a) Circuit diagram.
(b) Secondary voltage.
(c) Secondary current, in phase with secondary voltage.
(d) Secondary current, in phase-opposition to secondary voltage.
(e) Secondary current, lagging.
(c′), (d′) Commutating voltage, effective part.
1′ . . . 6′ : Valves conducting the positive half-wave of the secondary current.
1″ . . . 6″: Valves conducting the negative half-wave of the secondary current.

employing different primary voltages, the transformer secondary winding being modified accordingly.* The envelope form of the secondary voltage gives the name to the type of mutator convertor.

The secondary current i_s is determined by the secondary voltage v_s and the secondary load. In Fig. 3(*c*) the current i_s is assumed to be sinusoidal and lagging behind the voltage v_s. The diagram indicates how the current i_s is conducted in succession by the switches and the corresponding transformer secondary phases.

Returning to Fig. 1, the mercury-arc valves may be regarded as periodically operating switchgears. Two sets of valves are provided, since a mercury-arc valve permits current-flow in one direction only, and current has to be conducted in both directions. Grid-control prevents flow of current when it is necessary for a valve to be non-conductive.

The operation of the valves is illustrated in Fig. 4. Fig. 4(*a*) gives the circuit diagram of the mutator convertor, the arrangement being identical with that in Fig. 1. Fig. 4(*b*) shows the diagram of the secondary voltage v_s. Figs. 4(*c*), 4(*d*), and 4(*e*) represent the secondary current i_s with various phase displacements. The numbers 1 to 6 indicate the phases of the transformer secondary winding, v_1 to v_6 being the respective voltages. The numbers 1′ to 6′ refer to the valves which conduct the positive part of the secondary current. The negative part of the secondary current flows through the valves 1″ to 6″. Hatching marks co-ordination of valves and half-waves of the secondary current.†

Commutation.

Each valve conducts a section of the secondary current i_s. Since conduction of current in a mercury-arc valve is accompanied by an arc in the valve, commutation from one valve to another one requires the arc in the first valve to be extinguished. This is obtained with a short-circuit current caused by the difference of the voltages of the two affected transformer secondary phases.

For example, let valve 2′ take over the current i_s from valve 1′ [see Fig. 4(*a*)]. When the anode of valve 2′ ignites, the voltage-difference v_2-v_1 (v_1 and v_2 being the voltages of the transformer secondary phases 1 and 2 respectively) causes a short-circuit current to flow through valve 1′ from cathode to anode.‡ The short-circuit current flows from the transformer secondary phase 2 through the valves 2′ and 1′ to phase 1, superimposing in valve 1′ to the current i_s, and increasing according to the reactance in the short-circuit path, until the total current through valve 1′ becomes zero. Reducing the valve current to zero results in the arc being extinguished.

Referring to Fig. 4(*b*), commutation at the point t_c means transfer from valve 1′ to valve 2′ in the case of Fig. 4(*c*), and transfer from valve 1″ to valve 2″ in the case of Fig. 4(*d*). In the first case, where the secondary current is in phase with the secondary voltage, a short-circuit current and, therefore, commutation, can start when the anode of valve 2′ becomes positive against the anode of valve 1′, e.g. when the voltage-difference v_2-v_1 becomes positive (rectifier* condition). In the second case, where the secondary current is in phase opposition, commutation must be completed before the anode of valve 2″ becomes negative against the anode of valve 1″, e.g. before v_2-v_1 becomes zero (invertor† condition). The shading lines in Fig. 4(*c′*) and Fig. 4(*d′*) indicate the effective part of the commutating voltage v_2-v_1 for rectifier and for invertor condition respectively.

Energy flow from the primary 3-phase network to the secondary single-phase network requires that commutation is performed according to rectifier condition. Energy flow in the opposite direction results in invertor condition for commutation. A current with a phase displacement as shown, for example, in Fig. 4(*e*) involves alternating directions of energy flow and, consequently, alternating commutating conditions.‡

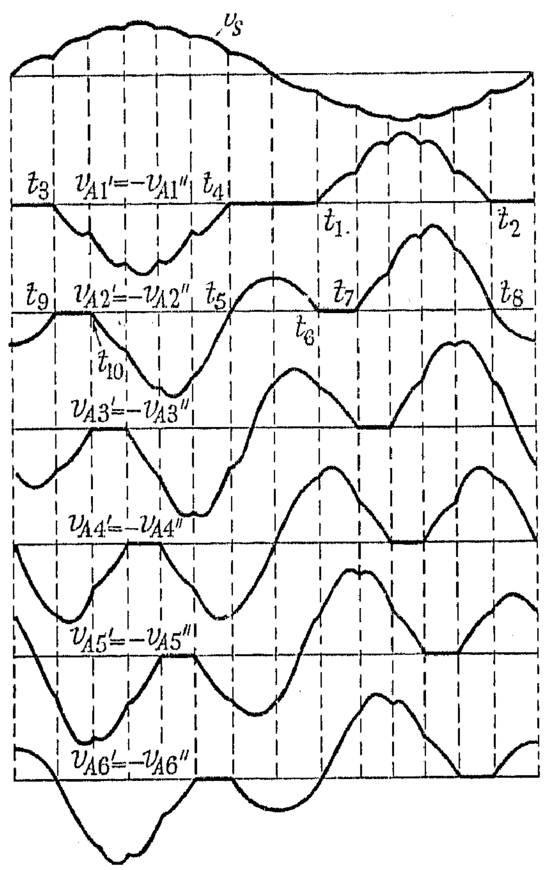

Fig. 5.—Voltages between anode and cathode of the valves of mutator convertor Fig. 4*a*.

$v_{A1'} \ldots v_{A6'}$: Voltages anode to cathode of the valves 1′ . . . 6′ respectively.

$v_{A1''} \ldots v_{A6''}$: Voltages anode to cathode of the valves 1″ . . . 6″ respectively.

Grid-control.

Grid-control of the mutator convertor has to fulfil the condition that each grid must block the corresponding anode during the interval in which the voltage between anode and cathode is positive and the anode is not permitted to ignite.

Fig. 5 shows the diagrams of the voltages between anode and cathode of the valves of Fig. 4(*a*), $v_{A1'}$ being the voltage of anode to cathode of valve 1′, $v_{A2'}$ being the voltage of valve 2′, and so on, and $v_{A1''} = -v_{A1'}$ being the anode-to-cathode voltage of valve 1″, and so on. The voltage between anode and cathode of a valve is the

* See Bibliography, (1). † *Ibid.*, (2).
‡ A mercury-arc valve conducting a current in the normal direction (anode to cathode) may simultaneously conduct a current in the opposite direction, provided that the current from cathode to anode is smaller than that from anode to cathode.

* For conversion of alternating to direct current.
† For conversion of direct to alternating current
‡ See Bibliography, (2).

difference of the voltage of the corresponding transformer phase and the secondary voltage; it is, for example, $v_{A1'} = v_1 - v_s$, $v_{A1'}$ being the anode-to-cathode voltage of valve 1′, v_1 the voltage of the transformer secondary phase 1, and v_s the secondary voltage.

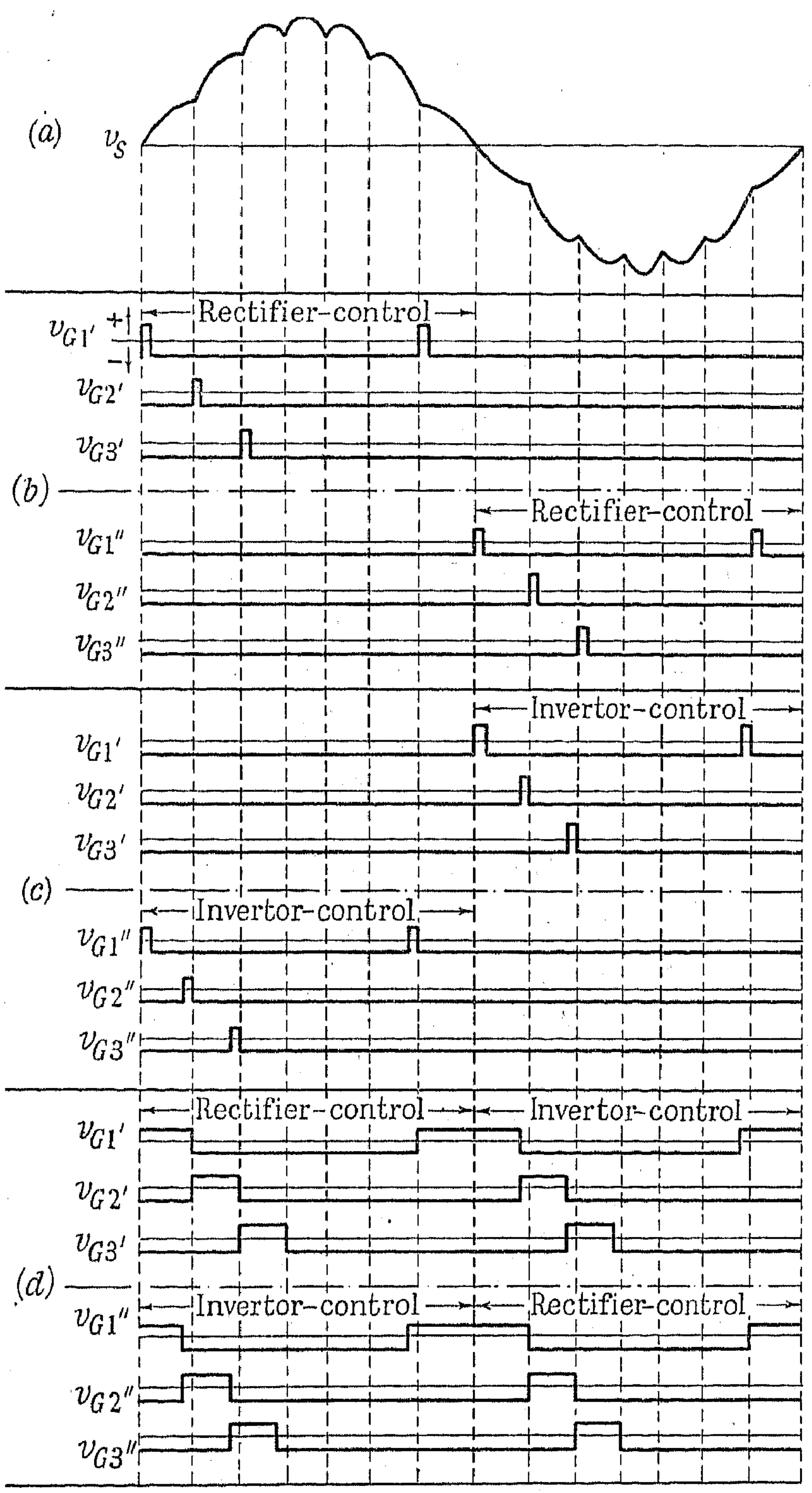

Fig. 6.—Scheme of grid-control of the mutator convertor Fig. 4*a*.

(a) Secondary voltage.
(b) Grid potentials when secondary current in phase with secondary voltage (rectifier operation of the valves).
(c) Grid potentials when secondary current in phase opposition to secondary voltage (invertor operation of the valves).
(d) Grid potentials for any phase displacement of the secondary current (mixed operating conditions).

$v_{G1'} \ldots v_{G3'}$: Grid potentials of valves 1′ . . . 3′.
$v_{G1''} \ldots v_{G3''}$: Grid potentials of valves 1″ . . . 3″.

According to Fig. 5 the voltage $v_{A1'}$ of valve 1′ is positive from t_1 to t_2, and the voltage $v_{A1''}$ of valve 1″ is positive from t_3 to t_4. The grid of valve 1′ must, therefore, have blocking potential from t_1 to t_2, and the grid of valve 1″ must block from t_3 to t_4. The positive period of the voltage $v_{A2'}$ requires the anode of valve 2′ to be blocked from t_5 to t_6 and from t_7 to t_8, and the anode of valve 2″ from t_8 to t_9 and from t_{10} to t_5. The blocking conditions for the anodes of the other valves may be seen from the diagrams in Fig. 5.

In order to stabilize the operation of the mutator convertor, the blocking period of a grid is made longer than the blocking condition of the anode requires. Each grid is given blocking potential during the whole period during which the corresponding anode is not required to ignite. Fig. 6 illustrates the scheme of grid-control, Fig. 6(*a*) showing the diagram of the secondary voltage v_s, and Figs. 6(*b*), 6(*c*), and 6(*d*) representing the grid potentials of the valves 1′ to 3′ and 1″ to 3″ of Fig. 4(*a*) for various phase displacements of the secondary current. In order to simplify representation, the grid potentials of valves 4′ to 6′ and 4″ to 6″ are not shown.

In Fig. 6(*b*) it is assumed that the secondary current is in phase with the secondary voltage (rectifier operation). When an anode has to ignite, liberating voltage is applied to the corresponding grid according to rectifier condition. Since a mercury arc is independent of the grid potential once the arc has ignited, liberating voltage is applied for a short period only.

Fig. 6(*c*) shows the grid potentials which exist if the secondary current is in phase opposition to the secondary voltage. Commutation is according to invertor condition, and liberating voltage is applied at such a moment that commutation is completed before the commutating voltage [see, for example, Fig. 4(*d′*)] has become zero.

Fig. 6(*d*) indicates the grid potentials provided for any phase displacement of the secondary current. Each valve can meet every requirement of the secondary current. During the positive half-wave of the secondary voltage v_s the anodes 1′ to 6′ are rectifier-controlled, and simultaneously the anodes 1″ to 6″ are invertor-controlled. During the negative half-wave of v_s there is invertor control for the anodes 1′ to 6′, and rectifier control for the anodes 1″ to 6″.*

Arrangements with multiple-anode vessels.

Fig. 7 shows two circuit diagrams of the mutator convertor equipped with multiple-anode mercury-arc vessels. In Fig. 7(*a*) the transformer has two 6-phase secondaries, each forming a working unit with a 6-anode mercury-arc vessel. Unit I produces the positive half-wave i_{sI} of the secondary current, and unit II produces the negative half-wave i_{sII}, both half-waves being combined to form the full-wave current i_s by " cross "-arrangement of the two units.

Fig. 7(*b*) illustrates a " push-pull "-arrangement of the two working units I and II. An additional transformer with a 2-phase primary is provided to combine the two half-waves i_{sI} and i_{sII} to form the full-wave current i_s.

In both multiple-anode arrangements the anodes of the mercury-arc vessels operate as the anodes of the single-anode valves in Fig. 4(*a*), the numbers 1′ to 6′ and 1″ to 6″ in Fig. 7 and Fig. 4(*a*), respectively, indicating equivalent anodes. The two transformer secondaries of a multiple-anode mutator convertor are arranged in parallel, the second winding being necessary in order to bring the cathodes of the valves 1″ to 6″ of Fig. 4(*a*) to an equal potential in Fig. 7.†

* See Bibliography, (2, 3).

† *Ibid.*, (2).

Variable frequency ratio.

The frequency ratio of secondary and primary voltages of a mutator convertor according to Fig. 1 or Fig. 7 is fixed at 1 : 3. The principle of obtaining a variable frequency ratio is indicated in Fig. 8, which shows the curve of the secondary voltage v_s of a mutator convertor with equal primary voltages v_1 to v_6. Fig. 8(*a*) represents the secondary voltage v_s with the basic frequency ratio 1 : 3; 7 individual primary voltages form one half-wave of the secondary voltage. In Fig. 8(*b*) the length of the half-wave of the secondary voltage v_s is shortened by reducing the number of individual primary voltages to 6. In Fig. 8(*c*) the length of the half-wave is extended by increasing the number of individual primary voltages to 8. In the first case, where the half-wave is shortened, the secondary frequency is increased by 12·5 %; in the second case the frequency is reduced by 10 % compared with the basic frequency according to Fig. 8(*a*).

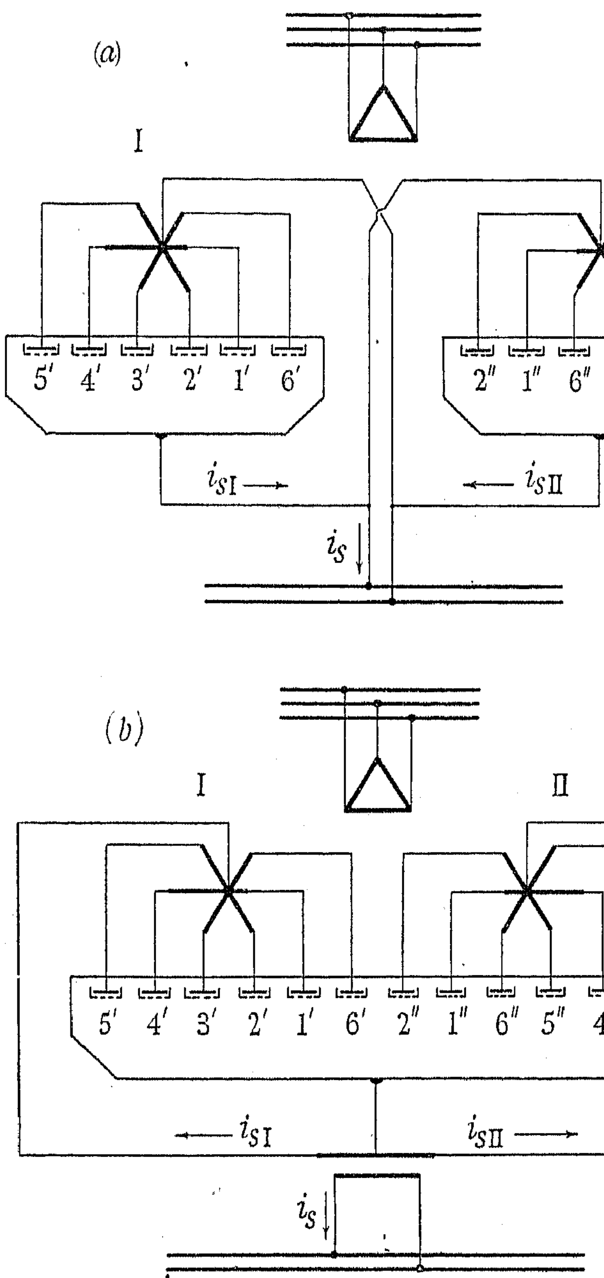

Fig. 7.—Mutator convertor of the envelope curve type with multiple-anode mercury-arc vessels.

(a) " Cross " arrangement of the mutator convertor.
(b) " Push-pull " arrangement of the mutator convertor.
I: Unit producing the positive half-wave i_{sI} of the secondary current.
II: Unit producing the negative half-wave i_{sII} of the secondary current.

Fig. 9 shows the circuit diagram of electromechanical grid-control* for a mutator convertor with variable frequency ratio, producing the voltage curve v_s of Fig. 8. Transformer and mercury-arc vessels are arranged in accordance with Fig. 7(*a*).

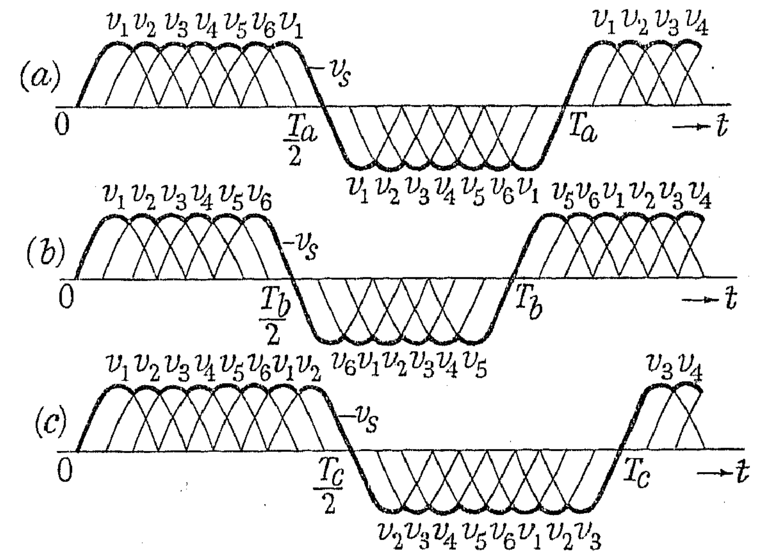

Fig. 8.—Change of frequency of the secondary voltage of a direct-coupling mutator convertor.

(a) Basic frequency.
(b) Secondary frequency increased by 12·5 %; $T_b = \frac{8}{9}T_a$.
(c) Secondary frequency reduced by 10 %; $T_c = \frac{10}{9}T_a$.

The grid-control equipment consists of two batteries B'_- and B''_- supplying the blocking voltages for the grids, two batteries B'_+ and B''_+ supplying the liberating voltages, and rotary switches driven by the motors S and P. The motor S runs synchronously with the secondary frequency, while the motor P drives its rotary switch arrangement synchronously with the primary frequency.

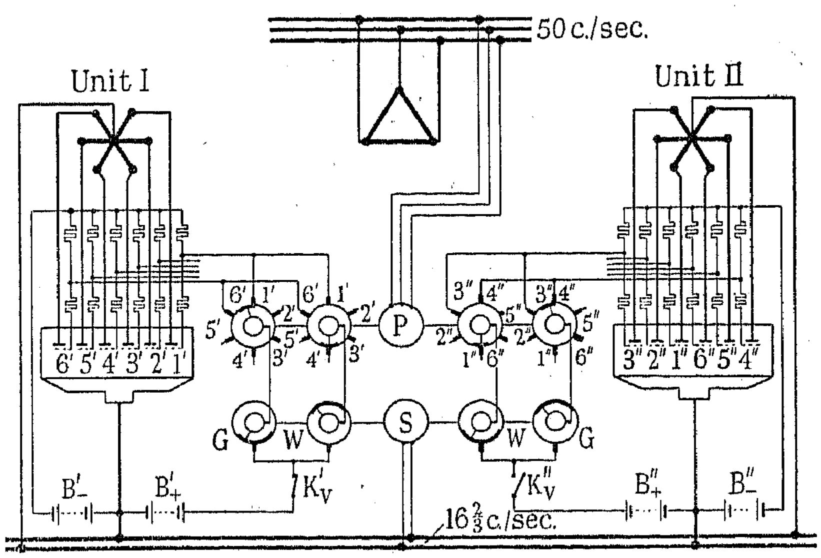

Fig. 9.—Grid-control of the direct-coupling mutator convertor with variable frequency (electromechanical control).

B'_-, B''_-: Batteries supplying blocking voltages.
B'_+, B''_+: Batteries supplying liberating voltages.
P: Motor running synchronously with primary frequency and driving primary rotary switch arrangement.
S: Motor running synchronously with secondary frequency and driving secondary rotary switch arrangement.
G: Control according to rectifier conditions.
W: Control according to invertor conditions.
K'_v, K''_v: Arrangement for mutual blocking.

Fig. 10 illustrates the closing periods of the contacts

* Electrical grid-control operates according to the same principle, employing gas-discharge valves and primary and secondary alternating voltages instead of mechanical contacts.

on the rotary switches, K'_1–K'_6 being the primary contacts and K'_s the secondary contacts for unit I of Fig. 9; K''_1–K''_6 and K''_s are primary and secondary contacts respectively for unit II. G indicates the contacts for rectifier control of the mutator convertor, and W the control for invertor operation.

The secondary contacts K'_s and K''_s control the number of individual primary voltages taking part in the formation of the secondary voltage. Fig. 10 shows the closing periods of the contacts K'_s and K''_s for a frequency ratio of 1 : 3. The closing periods are reduced if the secondary

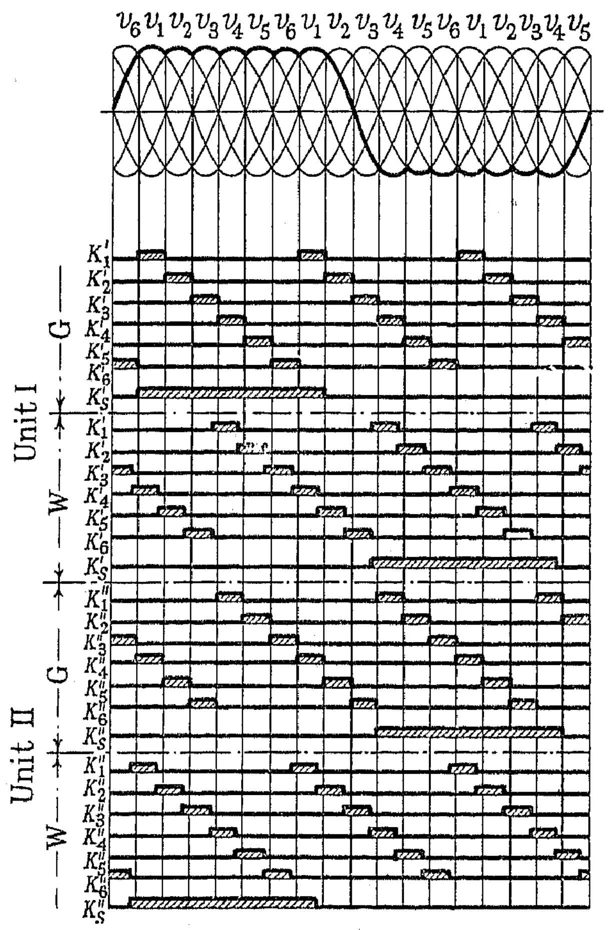

Fig. 10.—Closing periods of the rotary switches of Fig. 9.

$K'_1 \ldots K'_6$: Contacts of the primary rotary switches operating for unit I.
$K''_1 \ldots K''_6$: Contacts of the primary rotary switches operating for unit II.
K'_s, K''_s: Contacts of the secondary rotary switches operating or unit I and unit II respectively.
G: Control according to rectifier conditions.
W: Control according to invertor conditions.

frequency is greater than one-third the primary frequency, and increased for a smaller secondary frequency.*

The additional contacts K'_v and K''_v in Fig. 9 are arranged to stabilize operation of the mutator convertor. Contact K'_v is closed and contact K''_v is open when unit I of the mutator convertor is producing its half-wave of the secondary current. On the other hand, contact K''_v is closed and contact K'_v is open when unit II is operating for the other half-wave of the secondary current. Both contacts are controlled by the secondary current, normal operation of one unit blocking any faulty operation of the other unit.†

The grid-controlled mutator convertor.

The grid-controlled mutator convertor is an arrangement with the same circuit diagram and operating conditions as the mutator convertor of the envelope curve type, the only difference being equal voltages on the transformer secondary phases. The basic form of the secondary voltage of the grid-controlled mutator con-

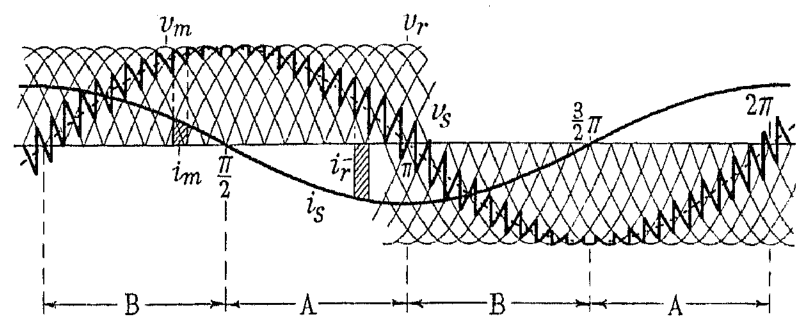

Fig. 11.—Secondary voltage of the grid-controlled mutator convertor supplying 90° leading current.

v_m; v_r: Voltages of the mth and rth phase respectively of the transformer secondary winding.
v_s: Secondary voltage of the mutator convertor.
i_m, i_r: Currents in the mth and rth phase respectively of the transformer secondary winding.
i_s: Secondary current.
A: Range of invertor operation of the mutator convertor.
B: Range of rectifier operation of the mutator convertor.

vertor is identical with Fig. 8, the secondary frequency being variable. The actual form of the secondary voltage is indicated in Fig. 11, which represents the secondary voltage v_s of a 12-phase grid-controlled mutator convertor supplying a 90° leading current i_s.

The sinusoidal form of the secondary voltage is obtained from the basic form of Fig. 8 by influencing grid control: ignition of the anodes is retarded during rectifier operation of the mutator convertor, and accelerated during invertor operation. Fig. 11 shows that suitable sections of the equal primary voltages are cut out and joined to the approximately sinusoidal curve of the secondary voltage.

Grid control operates in principle as illustrated in Figs. 9 and 10, with an additional arrangement for retard-

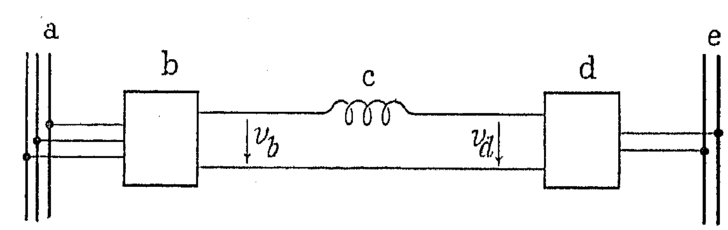

Fig. 12.—Fundamental arrangement of the mutator convertor with intermediate direct-voltage.

a: Primary 3-phase network, 50 c./sec.
b: Primary mutator, normally operating as rectifier; for energy recuperation operating as invertor.
c: D.c. circuit and choke coil.
d: Secondary mutator, normally operating as invertor; for energy recuperation operating as rectifier.
e: Secondary single-phase network, 16⅔ c./sec.
v_b: Primary direct voltage.
v_d: Secondary direct voltage.

ing rectifier ignition and accelerating invertor ignition of the anodes. In practical cases grid-control voltages are obtained by combining the voltages of primary and secondary networks.*

(b) Mutator Convertors with Intermediate Direct Voltage

Fundamental arrangement.

The fundamental arrangement of a mutator convertor with intermediate direct voltage is shown in Fig. 12.

* See Bibliography, (3). † F. Barz: Austrian Patent No. 135478.

* See Bibliography, (12, 13, 14).

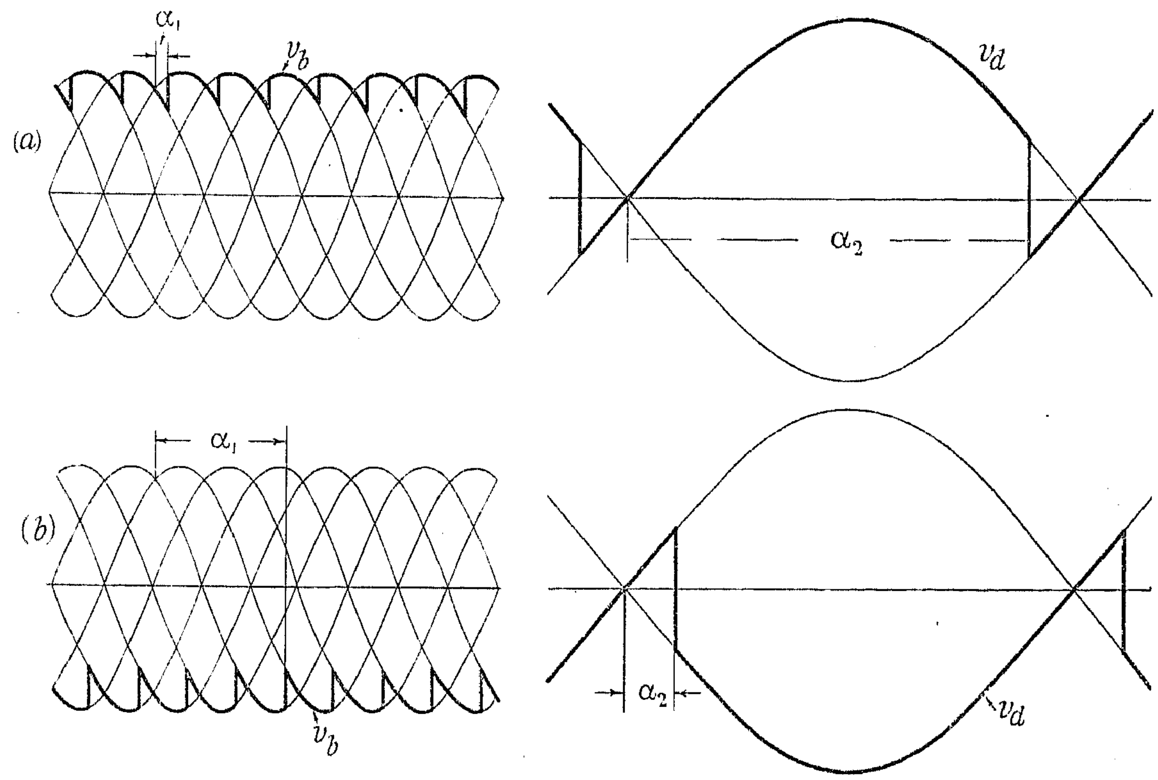

Fig. 13.—The direct voltages in the d.c. circuit of the mutator convertor with intermediate direct voltage.

(a) Primary mutator operating as rectifier and secondary mutator operating as invertor (normal direction of energy flow).
(b) Primary mutator operating as invertor and secondary mutator operating as rectifier (energy recuperation).
α_1: Ignition angle of primary mutator.
α_2: Ignition angle of secondary mutator.

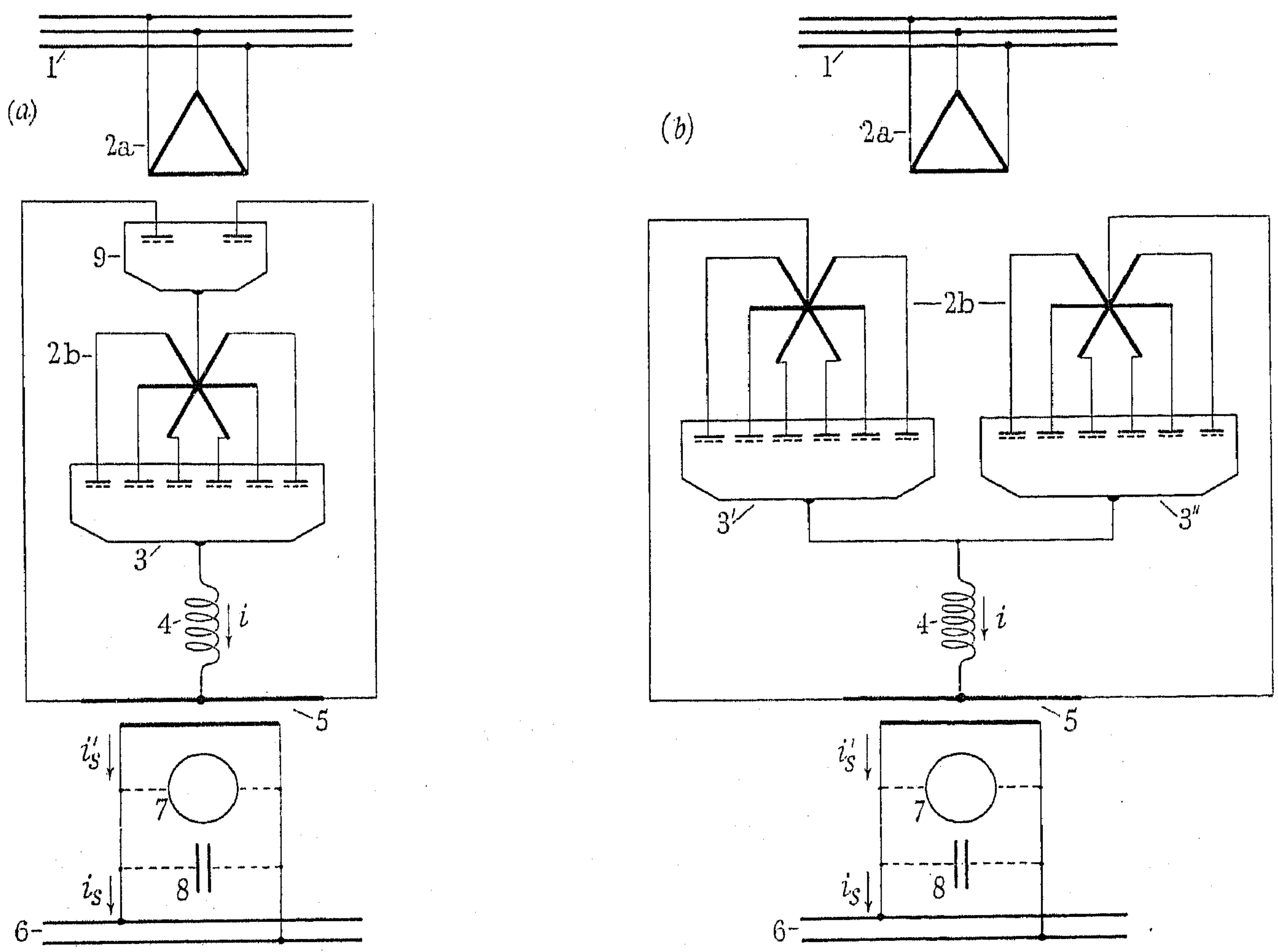

Fig. 14.—Circuit diagrams of the mutator convertor with intermediate direct voltage.

(a) Two-mutator arrangement (primary and secondary mutators separately).
(b) One-mutator arrangement (primary and secondary mutators combined).

1: Primary 3-phase network.
2: Input transformer (2a = primary, 2b = secondary).
3 3′, 3″: Mercury-arc vessels.
4: Choke coil.
5: Output transformer.
6: Secondary single-phase network.
7: No-load generator.
8: Condenser battery.
9: Two-anode mercury-arc vessel.
i: Direct current.
i_s': Output current from the mutator convertor.
i_s: Current to the secondary network.

The primary 3-phase network (a) and the secondary single-phase network (e) are coupled by the d.c. circuit (c), (b) and (d) being grid-controlled mercury-arc mutators. The mutator (b) operates normally as a rectifier converting 3-phase alternating current to direct current; mutator (d) operates as an invertor converting direct current to single-phase alternating current. Recuperation of energy from the secondary network, e.g. transfer of power from the single-phase network to the 3-phase network, sees mutator (d) as rectifier and mutator (b) as invertor.

The choke coil (c) is inserted between the two mutators to buffer the difference of the direct voltages v_b and v_d. The curves of v_b and v_d are given in Fig. 13 for a 6-phase arrangement of mutator (b) and a 2-phase arrangement of mutator (d), Fig. 13(*a*) representing the direct voltages for the normal energy direction, and Fig. 13(*b*) showing the direct voltages for recuperation of energy from the single-phase network.*

Circuit diagrams.

Fig. 14(*a*) gives the circuit diagram of the mutator frequency-convertor, consisting of two separate mutators with intermediate d.c. circuit according to Fig. 12. The input transformer with primary (2a) and secondary (2b), and the mercury-arc vessel (3), form the primary mutator (b) of Fig. 12. The output transformer (5) and the mercury-arc vessel (9) correspond to the secondary mutator (d).

Referring to Fig. 14(*a*), the direct current i flows from the cathode of vessel (3) through the choke coil (4) to the mid-point of the primary of transformer (5), and is conducted alternately through the left-hand phase and the right-hand phase of the primary. The secondary of output transformer (5) supplies an alternating current to the secondary network (6). The anodes of vessel (9) conduct the direct current alternately, commutation being performed with the alternating voltage of the secondary network.

Fig. 14(*b*) shows the circuit diagram of the mutator convertor equipped with one mutator only. The arrangement has two secondaries (2b) on the input transformer and two mercury-arc vessels (3′) and (3″). The vessels (3′) and (3″) operate alternately, supplying an uninterrupted flow of direct current i through the choke coil (4) to the mid-point of output transformer (5). Each vessel works normally as rectifier, power being transmitted from the 3-phase network to the single-phase network. For energy exchange in the reverse direction each vessel works as an invertor. Commutation from one vessel to the other is performed with the alternating voltage of the secondary network, commutation being according to invertor condition for energy flow from the 3-phase network to the single-phase network, and according to rectifier condition for the reverse direction of energy flow.

Commutation of the anodes of vessel (9) in Fig. 14(*a*) or commutation from vessel (3′) to vessel (3″) and vice versa [Fig. 14(*b*)] requires an alternating e.m.f. in the secondary network. If there is no generator in the secondary network, the e.m.f. has to be provided by inserting a no-load generator (7) or a condenser battery (8) on the secondary side of the mutator convertor (see Fig. 14).

* See Bibliography, (15).

Another function of generator (7) or condenser (8) will be understood from Fig. 15. Fig. 15(*a*) shows the secondary voltage v_s, while Fig. 15(*b*) represents the output current i_s' from the mutator convertor, smooth direct current in the intermediate d.c. circuit being assumed. The harmonics of the output current have to be absorbed by generator (7) or condenser (8).

As a consequence of commutation the fundamental wave i_f of the output current i_s' contains a 90° leading component* [see Fig. 15(*b*)]. The load on the traction supply mains is, however, inductive. Generator (7) or condenser (8) has, therefore, also to absorb the 90° leading component of the fundamental wave i_f. In

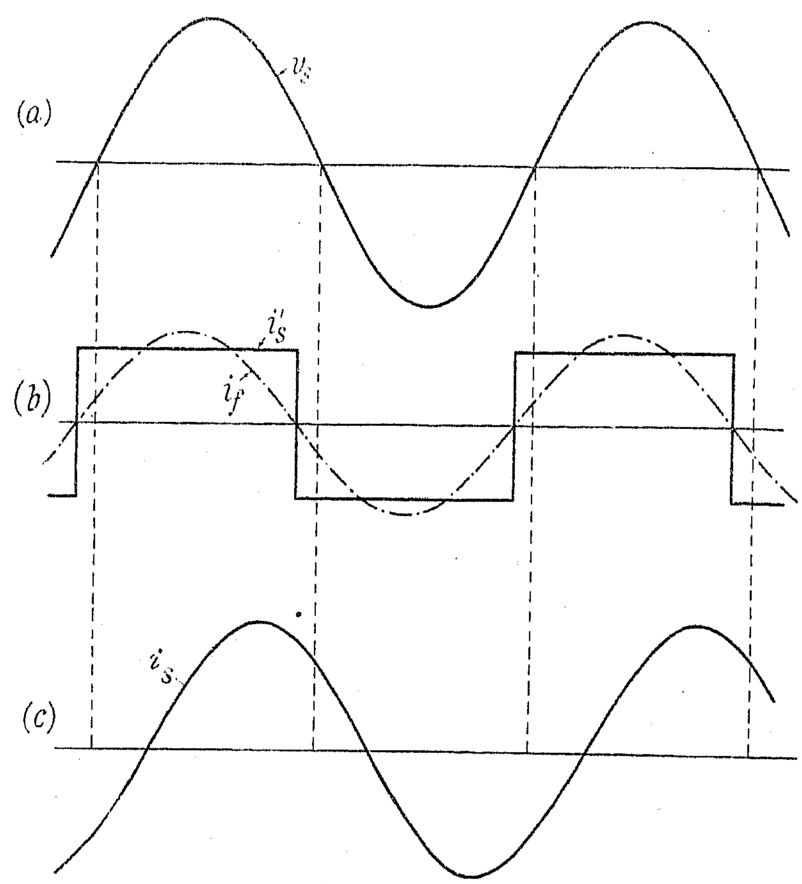

Fig. 15.—Voltage and currents on the secondary side of the mutator convertor with intermediate direct voltage.

(a) Secondary voltage.
(b) Output current from the mutator convertor.
(c) Current to the secondary network.

addition they† have to supply the 90° lagging component of the secondary current i_s [Fig. 15(*c*)].‡

Grid control.

For the mutator convertor with two separate mutators according to Fig. 14(*a*), grid control is applied to both mutators separately. One mutator has to be controlled as a rectifier, and the other mutator is controlled as an invertor. Change from rectifier to invertor operation of a mutator is obtained by retarding ignition of the anodes [see the ignition angle α_1 for voltage v_b in Figs. 13(*a*) and 13(*b*)]. Advancing the time of ignition transforms a mutator from invertor to rectifier operation [see ignition angle α_2 for voltage v_d in Figs. 13(*a*) and 13(*b*)].

The grid-control equipment of the mutator convertor

* For invertor operation commutation has to be completed before the commutating voltage v_s has become zero.
† Generator and condenser may operate in parallel with one another.
‡ See Bibliography, (15, 20).

[Fig. 14(b)] combines individual control of each anode and simultaneous control of the anodes of vessel (3′) and vessel (3″), respectively. Individual control of each anode is performed with the frequency of the primary 3-phase voltage, enabling each vessel to operate either as rectifier or invertor. Simultaneous control of the anodes determines which of the two vessels (3′) and (3″) is conductive; control is carried out with the frequency of the secondary voltage, phase displacement of control being according to invertor or rectifier requirement of commutation.

The direct-current circuit.

The intermediate d.c. circuit of the mutator convertor acts as the flexible coupling of 3-phase and single-phase networks. Primary and secondary voltages are independent of one another, and their frequency ratio is variable. Energy exchange is performed by grid control adjusting the mean values of the direct voltages in the d.c. circuit. Change from normal direction of power flow to energy recuperation is obtained by reversing the sign of the direct voltages with grid control (see Fig. 13).*

(3) REACTION ON THE PRIMARY NETWORK

General

The reaction of a mutator frequency-convertor on the primary 3-phase network will be understood if the power conditions for 3-phase energy supply to a single-phase system are considered. A 3-phase network with a symmetrical 3-phase voltage system normally supplies a constant power flow N as indicated in Fig. 16(a). Fig. 16(b) shows the power demand n of the single-phase network. The power demand oscillates at twice the secondary frequency, N being the mean value of power oscillation; n_a represents the active component and n_r the reactive component of power demand. The instantaneous power demands of the single-phase system and normal 3-phase supply are not equal.

* See Bibliography, (15).

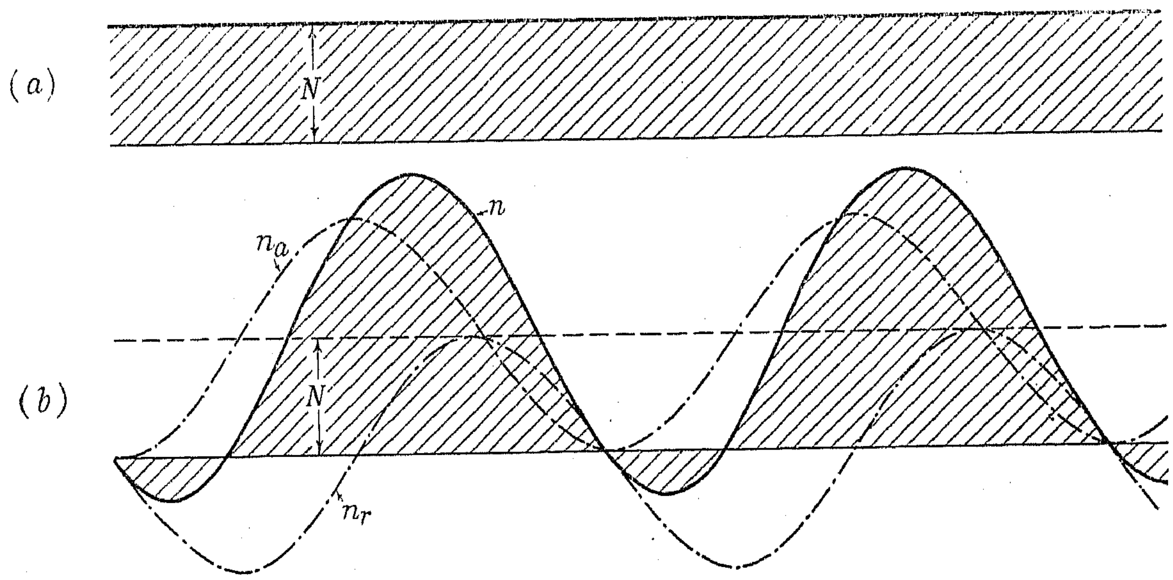

Fig. 16.—Power supply for conversion of 3-phase to single-phase alternating current.

(a) Power supply of a symmetrical 3-phase current system.
(b) Power demand of a single-phase system.
n: Single-phase power for cos $\phi_s = 0{\cdot}71$.
n_a: Active power component.
n_r: Reactive volt-ampere component.
N: Mean value of single-phase power demand.

The difference between the instantaneous power demands of the single-phase system and of the normal 3-phase supply may be balanced by an energy reservoir between primary and secondary networks;* the single-phase power oscillations will then not affect the 3-phase power supply. The fact that there is no energy reservoir in the convertor arrangement means that the single-phase power oscillations are transferred to the 3-phase network, involving harmonics, sub-harmonics, and a negative-sequence component in the 3-phase current system. The 3-phase currents are distorted, thus affecting the efficiency factor in the 3-phase supply.

The efficiency factor in the 3-phase supply indicates the ratio of active to mean apparent power of the 3-phase system. Let I_R, I_S, I_T be the 3-phase currents, differing from each other. The mean current I_m of the 3-phase current system† is

$$I_m = \sqrt{\left[\tfrac{1}{3}(I_R^2 + I_S^2 + I_T^2)\right]} \quad . \quad . \quad . \quad (1)$$

If V is the voltage-difference between two lines, the mean apparent power P_m is given by the expression

$$P_m = \sqrt{3}VI_m \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Let I_a be the active part of the positive-sequence component of the 3-phase current system; then

$$P_a = \sqrt{3}VI_a \quad . \quad . \quad . \quad . \quad . \quad (3)$$

represents the active power transmitted by the 3-phase system. The efficiency factor λ will now be

$$\lambda = \frac{P_a}{P_m} = \frac{I_a}{I_m} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

If I_r be the reactive part of the positive-sequence component of the 3-phase current system, the displacement

* The revolving masses of a rotating current convertor provide, for example, an effective energy reservoir.
† The heat loss produced in the three lines by the mean current I_m is equal to the heat loss produced by the three different currents I_R, I_S, I_T.

factor $\cos\phi$, indicating the reactive volt-amperes in the 3-phase system, is determined as

$$\cos\phi = \frac{I_a}{\sqrt{[I_a^2 + I_r^2]}} \quad . \quad . \quad . \quad . \quad (5)$$

The angle ϕ gives the displacement between the 3-phase voltage system and the positive-sequence component of the 3-phase current system. Introducing the fundamental wave factor

$$F = \frac{\sqrt{[I_a^2 + I_r^2]}}{I_m} \quad . \quad . \quad . \quad . \quad (6)$$

to represent the ratio of normal fundamental wave* $\sqrt{(I_a^2 + I_r^2)}$ to total current I_m, the efficiency factor may also be written, with equations (4), (5) and (6),

$$\lambda = F\cos\phi \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Equation (7) shows the influence of distortion of the 3-phase current system. According to equation (6) the fundamental wave factor F is unity for undistorted current. Distortion reduces F, and hence the efficiency factor λ. Transfer of the single-phase power oscillations to the 3-phase network results, therefore, in reducing the efficiency factor of the 3-phase supply.†

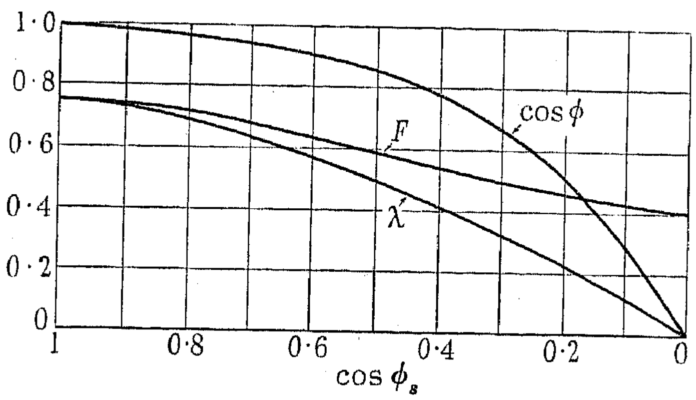

Fig. 17.—Reaction of a mutator convertor of the envelope curve type on the 3-phase system.

F: Fundamental wave factor.
cos ϕ: Displacement factor.
λ: Efficiency factor.
cos ϕ_s: Secondary displacement factor.

Direct-Coupling Mutator Convertors

A direct-coupling mutator frequency-convertor has no energy reservoir. The single-phase power oscillations are completely transferred to the 3-phase system. Fig. 17 shows the fundamental wave factor F, the displacement factor $\cos\phi$, and the efficiency factor λ, calculated for a 6-phase mutator convertor of the envelope curve type, for various values of the secondary displacement factor $\cos\phi_s$ and ideal conditions, e.g. sinusoidal secondary current, no overlapping (due to commutation), no power loss in the mutator convertor, and negligible magnetizing reactive volt-amperes.‡

It is interesting to note that the secondary reactive volt-amperes are conveyed in the primary network by sub-harmonics, harmonics, and a negative-sequence component of the 3-phase currents. The primary reactive volt-amperes are caused by phase displacement of the primary currents due to sections of primary voltages being cut out.

The ratio of 3-phase reactive volt-amperes to single-phase reactive volt-amperes for a mutator convertor of the envelope curve type is inversely as the frequency ratio of primary and secondary voltages,* magnetizing reactive volt-amperes and influence of commutation being neglected. For the frequency ratio 3 : 1 the ratio of reactive volt-amperes is 1 : 3. The primary reactive volt-amperes of an equivalent grid-controlled mutator convertor are, however, greater than the secondary reactive volt-amperes. The primary displacement factor and hence the efficiency factor of a grid-controlled mutator convertor are therefore smaller than the corresponding factors of an equivalent mutator convertor of the envelope curve type.†

Mutator Convertors with Intermediate Direct Voltage

The two types of mutator convertor with intermediate direct voltage are equal as regards their reaction on the 3-phase network. The no-load generator and/or the condenser on the secondary side of the mutator convertor, and the choke coil in the d.c. circuit, provide energy reservoirs which, acting jointly, prevent the single-phase power oscillations from passing to the 3-phase side. The 3-phase currents are therefore not affected by the single-phase power oscillations.

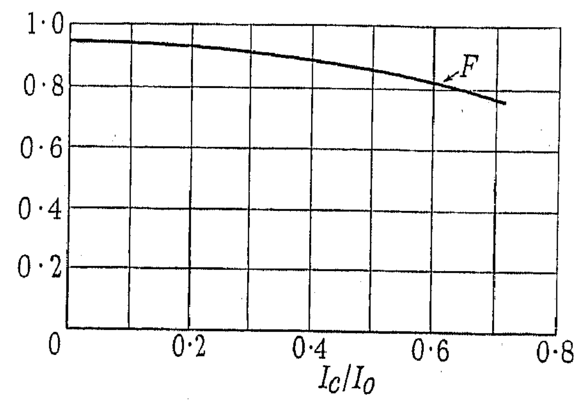

Fig. 18.—Reaction of a mutator convertor with intermediate direct voltage on the 3-phase system.

F: Fundamental wave factor in the 3-phase system.

There is, however, an energy fluctuation, with twice the secondary frequency, between the 3-phase network and the no-load generator and/or condenser. The energy fluctuation is caused by the alternating component of the secondary direct voltage (e.g. alternating component of voltage v_d in Fig. 12), and is transmitted through the d.c. circuit by the alternating component of the direct current. The inductance of the choke coil in the d.c. circuit determines the amplitude of the a.c. component and consequently of the power oscillation.

The alternating component of the direct current modulates the primary 3-phase currents and accordingly affects their fundamental wave factor. Fig. 18 shows the fundamental wave factor F, calculated for a 6-phase mutator arrangement, and plotted against the ratio I_c/I_0, where I_c is the r.m.s. value of the a.c. component and I_0 is the mean value of the direct current (neglecting the influence of overlapping due to commutation).

* The negative-sequence component of the 3-phase current system may be regarded as an abnormal fundamental wave.
† See Bibliography, (2, 15).
‡ *Ibid.*, (2).

* This relation is purely coincidental.
† See Bibliography, (18, 19, 20).

The primary displacement factor $\cos\phi$ of the mutator convertor is equal to the displacement factor of an equivalent grid-controlled rectifier supplying smooth direct current. For complete grid control the 3-phase efficiency factor λ of the mutator convertor is, therefore, identical with the fundamental wave factor F, if commutation effects are neglected.*

(4) MUTATOR CONVERTOR PLANTS

The Mutator Convertor at Basle

A mutator convertor of the envelope curve type for 3 600 kVA at $\cos\phi_s = 0\cdot 7$ (4 000 kVA for 30 min., 6 000 kVA for 1 min.) has been installed at Basle to energize the single-phase network of the Wiese Valley section of the German State Railways. Three-phase alternating current at 50 c./sec., 45 kV, is converted to single-phase, $16\frac{2}{3}$ c./sec., 16 kV, the frequency ratio 3 : 1 being fixed. The mutator convertor consists of two parts, each arranged according to Fig. 7(*b*), and producing a voltage similar to that shown in Fig. 8(*a*); series combination of the two voltages gives the sinusoidal form of the secondary voltage of the mutator convertor. The grid-control equipment consists of small transformers and thermionic valves operating as shown in Fig. 6(*d*). An additional thermionic valve, controlled by the 3-phase and single-phase currents of the mutator convertor, serves as a relay to block all grids simultaneously in the event of any overload, the relay interrupting the power supply.

When first switched on, the mutator convertor proved to be the source of serious disturbance of telephonic communication and radio reception. The single-phase line propagated low-frequency interference caused by the harmonics of the single-phase voltage; interference entered the telephone communication lines directly, and the radio receivers by the mains supply lead. The 3-phase lines radiated high-frequency waves produced in the mutator, and carried low-frequency interference caused by harmonics of the 3-phase currents and by oscillations in the 3-phase voltage.

Interference conducted by the single-phase line was remedied by installing filter circuits at the output terminals of the mutator convertor. The filter circuits reduce the amplitudes of the disturbing harmonics; on the other hand they increase the amplitudes of lower harmonics, thus distorting the single-phase voltage. Radiation of high-frequency waves from the 3-phase lines was reduced by providing high-frequency reactances in the 3-phase lines near the primary of the mutator transformer, and by earthing each anode through a condenser and resistance in series. Disturbance in telephone cable lines, which was caused by harmonics of the 3-phase currents, was cured by improving the telephone communication systems; asymmetrical telephone circuits were substituted by symmetrical arrangements. Oscillations in the 3-phase voltage, at the resonant frequency of the 3-phase network and caused by commutation of the mutator, had no disturbing effect since there were no overhead telephone lines near the 3-phase line.

Experimental investigation of the mutator convertor shows that the overall efficiency is $86\cdot 5$ % for $\frac{1}{4}$ load, $91\cdot 6$ % for $\frac{1}{2}$ load, $92\cdot 5$ % for $\frac{3}{4}$ load, $93\cdot 0$ % for full load, and $92\cdot 5$ % for $1\frac{1}{4}$ load. The fundamental wave factor F of the 3-phase currents is about $0\cdot 78$. The primary displacement factor $\cos\phi$ is about $0\cdot 8$ for $\frac{1}{2}$ load and $0\cdot 85$ for full load, and the efficiency factor λ is about $0\cdot 6$ and $0\cdot 65$, respectively, the secondary displacement factor $\cos\phi_s$ being $0\cdot 7$ to $0\cdot 8$.

Distortion of the single-phase voltage was found to affect the commutation of the traction motors only slightly. Experiments were carried out with the mutator-convertor voltage and with the undistorted voltage of a rotary frequency convertor.

Measurements on the 3-phase side of the mutator convertor indicated that the voltage distortion caused by the sub-harmonics of the 3-phase currents may be neglected if the mutator convertor does not take more than 5 % of the power of the generators of the 3-phase network.

Short-circuits of the mutator convertor were interrupted by the grid-control arrangement within $0\cdot 015$ sec. The short-circuit current had, therefore, no time to develop to full strength.

The mutator convertor has been in regular service since December, 1936. A rotary frequency convertor for 4 000 kVA has been provided as reserve. Data concerning reliability of service of the mutator convertor are not yet published.*

The Mutator Convertor at the Saalach Power Station

An experimental plant embodying a grid-controlled mutator convertor for 1 000 kVA was in operation from 1933 to 1935 at the Saalach power station of the German State Railways. Three-phase alternating current, 50 c./sec., 5 200 V, was converted to single-phase, $16\frac{2}{3}$ c./sec., 15 kV. The mutator convertor operated either alone, supplying energy for a section of the railway line, or in parallel with single-phase generators. In the first case the frequency ratio of primary and secondary voltages was fixed; in the second case it was variable.

The experiments showed that, when operating alone, the mutator convertor was able to meet the demands of traction load. In addition it was found that synchronization of the mutator convertor with single-phase generators and operation in parallel with them were easily controllable by adjusting the grid control accordingly. A mutator convertor plant for 3 750 kW has since been ordered by the German State Railways for coupling a 3-phase, 50-cycle high-voltage grid system with a 100-kV, single-phase, $16\frac{2}{3}$-cycle supply network.†

The Mutator Convertor at Pforzheim

A mutator convertor with intermediate direct voltage for 3 150 kW, arranged with one mutator according to Fig. 14(*b*), has been installed at Pforzheim for the German State Railways to couple the 100-kV, $16\frac{2}{3}$-cycle, single-phase network with the 220-kV, 50-cycle, 3-phase grid system. The mutator convertor is not yet in normal service.‡

* See Bibliography, (15, 20).

* See Bibliography, (6, 7, 8, 9, 10, 11).
† *Ibid.*, (14).
‡ *Ibid.*, (16).

(5) CONCLUSIONS

Comparison of the Various Mutator Convertors

Each type of mutator frequency-convertor has its advantages, but none is perfect.

The direct-coupling mutator convertor is self-contained, e.g. the mutator convertor can operate without a single-phase e.m.f. and can supply the secondary reactive volt-amperes. The mutator convertor with intermediate direct voltage cannot, however, operate without an e.m.f. and without an energy reservoir on the single-phase side; a no-load generator and/or a sufficient capacitance must therefore be provided on the secondary side if the mutator convertor is not operating in parallel with single-phase generators.

Reaction on the 3-phase network gives the mutator convertor with intermediate direct voltage an advantage. The primary fundamental wave factor F, indicating distortion of the 3-phase currents, is about $0 \cdot 9$ to $0 \cdot 93$ for the mutator convertor with intermediate direct voltage, and about $0 \cdot 75$ for the direct-coupling mutator convertor, the secondary displacement factor ϕ_s being about $0 \cdot 7$ to $0 \cdot 8$. The primary displacement factor $\cos \phi$ is in the first case usually near unity, and in the second case about $0 \cdot 8$ to $0 \cdot 85$ for the envelope curve type and about $0 \cdot 6$ to $0 \cdot 7$ for the grid-controlled type. The primary efficiency factor λ is, therefore, for the mutator convertor with intermediate direct voltage about 40 % higher than the corresponding value of the mutator convertor of the envelope curve type, and about 80 % higher than the efficiency factor of the grid-controlled mutator convertor.

The characteristics of the envelope curve mutator convertor are naturally fixed, frequency and amplitude of the secondary voltage being in constant ratio to the corresponding value of the primary voltage.* The grid-controlled mutator convertor and the mutator convertor with intermediate direct voltage are flexible, frequency and amplitude ratio of primary and secondary voltages being variable. The practical value of flexibility depends upon the conditions in the various primary and secondary networks, e.g. how far it is necessary to provide the possibility of deliberately influencing the exchange of energy between various points of the secondary network.

The efficiencies of the various types of mutator convertor are approximately the same. The type with intermediate direct voltage may cost more than the other types; on the other hand its grid-control equipment and maintenance may be less expensive.

Comparison with Rotary Convertors

The mutator convertors are in competition with rotary convertors, which have reached a high standard of performance.

The advantages of a mutator convertor are its higher efficiency, quiet running, easy operation with the aid of grid control, small weight of the equipment, and reduced costs for housing and foundations.

The disadvantages of a mutator convertor are mainly its reaction on the 3-phase network by distorting the 3-phase currents and having a lower efficiency factor. Distortion of the 3-phase voltage and interference with telephone communication and wireless reception may be kept at a sufficiently low level. Reduced efficiency factor in the supply system counterbalances to some degree the gain in the efficiency of current conversion, especially in the case of the direct-coupling mutator convertor.

Distortion of the primary voltage by the harmonics and sub-harmonics of the primary currents makes it necessary for the power supplied to the mutator convertor to be only a small proportion of the 3-phase power installation. Oscillations caused by commutation of the mutators draw attention to the conditions of resonance in the primary network.

Future Development

The future development of frequency-changing convertors for traction purposes depends largely upon future demands for coupling the existing $16\frac{2}{3}$ c./sec. supply systems with 50 c./sec. 3-phase grid systems, and upon future needs for conversion of 3-phase alternating current at 50 c./sec. to single-phase at $16\frac{2}{3}$ c./sec.

Alternating voltage at low frequency for traction purposes was necessary at the time when railway electrification was introduced, as commutation of the a.c. commutator motors did not then allow the use of 50 c./sec. Possibilities for the immediate use of this frequency for railways have, however, been created by recent developments.

There are various ways in which 50-cycle single-phase alternating current can be used on railways. In one case the single-phase voltage is converted on the locomotive to 3-phase by employing a specially designed convertor.* In another case conversion of single-phase to 3-phase is performed on the locomotive with a combination of two motors, one a single-phase motor with intermediate 3-phase rotor, and the other a 3-phase motor.† One firm has concentrated on developing a single-phase commutator motor for 50 c./sec.‡ In another case a rectifier is used on the locomotive and d.c. motors are employed.§ A further scheme is to use a single-phase motor the commutating part of which consists of a mercury-arc mutator,‖ or to employ a mutator convertor on the locomotive for changing from single-phase to 3-phase current.¶

On the other hand it must be noted that direct current of high voltage is a strong competitor for traction purposes. Rectifier substations offer a simple means of taking energy from 3-phase grid systems. The efficiency factor in the 3-phase lines is high, since the single-phase power oscillations are eliminated. A voltage of 3 000

* Control of the amplitude of the secondary voltage of the mutator convertor of the envelope curve type is possible according to the principles of the grid-controlled mutator convertor, e.g. the voltage may be reduced by adjusting the time of ignition of the anodes. Change of frequency ratio, the principle of which has been explained in connection with Fig. 8, involves precautions to avoid fluctuations of the secondary voltage.

* L. v. Verebélÿ: "Electrotechnical Fundamentals of a New Phase-Changing System for Electrification of Main Railway Lines," *Elektrotechnische Zeitschrift*, 1925, vol. 46, p. 37.

† L. Schön: "The Krupp Electrical Locomotive System for the Hell-Valley Railway," *Elektrische Bahnen*, 1937, vol. 13, p. 86.

‡ P. Herrmann: "The Electric Locomotive of the Siemens–Schuckert Works for the Hell-Valley Railway," *ibid.*, 1937, vol. 13, p. 77.

§ H. Hermle and A. Partzsch: "The Electrical Equipment of the AEG-Rectifier Locomotive for the Hell-Valley Railway," *ibid.*, 1937, vol. 13, p. 59.

H. Hutt: "The Electrical Equipment of the Brown Boveri Co. Rectifier Locomotive (Series E 244, No. 11), *ibid.*, 1937, vol. 13, p. 68.

‖ E. Kern: "The Commutatorless Single-Phase Locomotive Motor for 40 to 60 c./sec.," *ibid.*, 1931, vol. 7, p. 313.

¶ F. Kövessi, jun.: "A Mutator Single-Phase/3-Phase System for Traction Purposes," *ibid.*, 1936, vol. 12, p. 323.

volts in the d.c. system is already common. Perhaps future developments will lead to further increase of the voltage in the d.c. network, to about 15–20 kV, and to the use of mutator d.c. transformers or mutator d.c. motors on the locomotives.

Whatever the position of mutator frequency-convertors may be in the future, the existing plants are fine examples of modern electrical engineering.

It may be pointed out that the practical development of this interesting subject* was due to the initiative of Dr. O. Löbl.†

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* There are various earlier inventions referring to frequency-changing with arrangements employing electronic discharge devices. The invention of A. T. Kasley (U.S.A. Patent No. 1193485, filed September 14, 1909) describes a frequency convertor employing a rotating mercury jet for switching, and operating on the principle of the mutator convertor of the envelope curve type. An extensive list of patents may be found in the paper by K. Strobl entitled "Survey of Development of Mutator Frequency Convertors" (*Elektrotechnik und Maschinenbau*, 1939, vol. 57, p. 39).

† See Bibliography, (1).

‡ A nearly complete list of all papers (up to 1937) concerning frequency-changing with mercury-arc mutators may be found in *Elektrische Bahnen*, 1937, vol. 13, p. 229.

DEFORMATION OF TURBO-ALTERNATOR ROTOR WINDINGS, DUE TO TEMPERATURE RISE*

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(*Paper received* 4*th November*, 1938.)

SUMMARY

The paper deals with a problem of axial deformation of the rotor windings of turbo-alternators having long rotors. This trouble has only been experienced in recent years, and while the cause has been referred to by other authors the reasons why only a part of the winding has been affected have not been explained.

The present paper deals with the effect of temperature on the amount of deformation of different conductors throughout the depths of the slots, and shows that a comparatively small increase in temperature-rise may cause the deformation to become serious. A graphical method is given by which it is possible to determine whether a given temperature-rise will cause the deformation to become serious.

The effect of different methods of applying excitation is set forth.

In designing turbo-alternator rotors considerable thought has been given to the necessity of supporting the winding against collapse of individual coils and also to provide sufficient flexibility in order to allow room for expansion due to temperature-rise of the windings. For this purpose packing blocks are inserted between the rotor body and coil next to the rotor and also between individual coils. The longest coil, that is the one farthest away from the rotor, is supported by a heavy steel plate which in turn is secured by a nut on the shaft. This construction has been eminently successful in that no troubles due to collapse of the coils have been experienced.

During operation a large turbo-alternator developed vibrations necessitating an investigation, and on removing the retaining ring it was found that a certain number of the coils had distorted in a peculiar manner which had not been experienced previously. Examination of the rotor revealed that some of the turns had become shorter on certain coils only, whereas other coils were not affected at all.

The top turns, i.e. those nearest to the periphery, were not affected, the deformation having taken place on the lower portion of the coils. At first sight it appears inexplicable that such deformation could occur, and no reason could at first be found which would explain why some turns in the same slot should shorten and others not, but investigation shows that the phenomenon is due to a combination of temperature expansion and centrifugal forces, the latter exercising a restraining influence which prevents free expansion of the copper during running, thus causing stresses above the elastic limit of the copper. This restraining force is, of course, removed when the machine comes to rest, but permanent distortion which has taken place during running remains, and this distortion is repeated each time the machine is started and stopped, so that although the distortion each time is small, repeated starts and stops increase the deformation until in some cases it becomes larger than the clearance between individual coils, and short-circuits between coils occur. Similar troubles have been experienced in other countries. The cause has been discovered, but the reason why only a portion of the winding should be affected is not clear.

It may therefore be of interest to consider in detail what happens when a machine is started up cold and the excitation is applied after full speed is reached.

When current is applied to the rotor winding the copper heats up and would expand if free to do so, but if restrained from doing so it will contract at first elastically, and if the temperature is high enough so as to cause a stress above the elastic limit permanent deformation will take place. The longitudinal deformation will spread the conductor as there is always clearance sideways in the slot, and it may also thicken to some extent.

In order to simplify the problem the author proposes to neglect the influence of the end windings and consider only the slot portion. In actual practice the end windings will increase the restraining force, but as the retaining rings are not absolutely solidly fixed this force can be neglected.

Consider then the conductors in the slot. They are all subjected to centrifugal force in a varying degree dependent on their positions with reference to depth in the slot. The centrifugal force on the bottom conductor is that due to its own weight only. The restraining force against axial movement is, of course, due to friction. At the end of the rotor body there is then no axial restraining force at all, but as we move along the rotor towards the centre the copper is subjected to an increasingly greater restraining force so that if the length of the rotor is great enough we arrive at a point where the force is sufficient to hold the copper and thus prevent the expansion.

The second conductor will be subjected to a centrifugal force due to its own weight plus that of the first conductor, and the succeeding conductors will have a centrifugal force on them equal to that of their own weight plus the weight of all the conductors situated lower in the slot. The centrifugal force on the top conductor will then be equal to that due to all the copper in the slot, in addition, of course, to the weight of the mica insulation between turns, which is negligible.

* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.

† Metropolitan-Vickers Electrical Company, Ltd.

The expansion force acting on the individual turns is increased in the same way. The force on the bottom conductor is transmitted by friction to the second conductor, and the force from these two is transmitted to the third conductor, and so on until the top conductor is reached. The expansion force acting on this conductor will then be almost equal to the total expansion force of all conductors in the slot and is, of course, taken up by the wedge at the top of the slot. Calculations show that on large-diameter rotors a considerable portion of the windings in the centre are held with sufficient force to prevent expansion.

The temperature-rise of the copper above that of the rotor body at any specific excitation current is due to the temperature-drop through the insulation. This temperature-drop is dependent, as is well known, on the thickness and heat conductivity of the slot insulation. Due allowance has, of course, to be made for the clearance which has to be allowed in order to get the coils into the slots.

The heat generated in the coils raises the temperature of the rotor body, and as the volume of metal to be heated is very large in comparison with the total heat generated, the time taken for the body to reach maximum temperature is several hours. Also, as the temperature difference between copper and rotor body is practically constant except for a short interval of time at the beginning of application of excitation when this difference is less, the time taken for the copper to reach the final temperature is the same as for the rotor body. In general, final temperature in modern well-ventilated turbo-generators is reached in approximately 4 hours.

Let us now consider what takes place in regard to the expansion of the copper and steel due to temperature. The copper tends to expand and at the same time the rotor body will expand, but, of course, to a smaller extent.

The differential expansion between copper and steel which is of interest to us is due to two factors, (*a*) the higher temperature and (*b*) the greater coefficient of expansion of the copper. The linear coefficient of copper has been taken as 0·000017, and of steel as 0·0000115 per deg. C.

It will be clear that while the rotor body is free to expand this is not so in the case of the copper, as the centrifugal force will restrain it if this force is high enough to produce a friction force sufficient to balance the expansion force.

The centrifugal force is readily ascertained, whereas the value of the friction coefficient is somewhat difficult to evaluate with any degree of accuracy, but it would appear that a coefficient of 0·3 may be taken as reasonable.

From these general considerations it would be possible to build up a satisfactory theory explaining the deformation which has occurred. The point most difficult to explain is the movement of the lower turns of the winding when the top turns do not show any contraction. This phenomenon can only be explained satisfactorily by a considerably higher temperature of the turns occupying the lower portion of the slot. Calculations of temperature distributions are exceedingly difficult as no general method can be employed and it is therefore necessary to employ step-by-step methods in order to balance losses and heat flow. Calculations have been made for typical machines, and the results obtained indicate a maximum temperature variation throughout the depth of the slot of about 10 deg. C. This variation has of course, been obtained in the usual way by estimating the heat drop in the tooth due to the heat flowing from the winding through the insulation and then to the surface of the rotor. Such a small temperature difference would not be sufficient to cause the trouble experienced, and no satisfactory theory could be evolved on these premises.

When stripping the rotor which had given trouble, it was found that it was difficult to remove the conductors in the top portion of the slot, whereas those in the lower part of the slot were much easier to move. This was found to be due to the fact that the bonding material which is used in building the mica had been thrown out towards the top of the slot by centrifugal force, thus leaving an air space between the copper and the mica cell in the lower part of the slot.

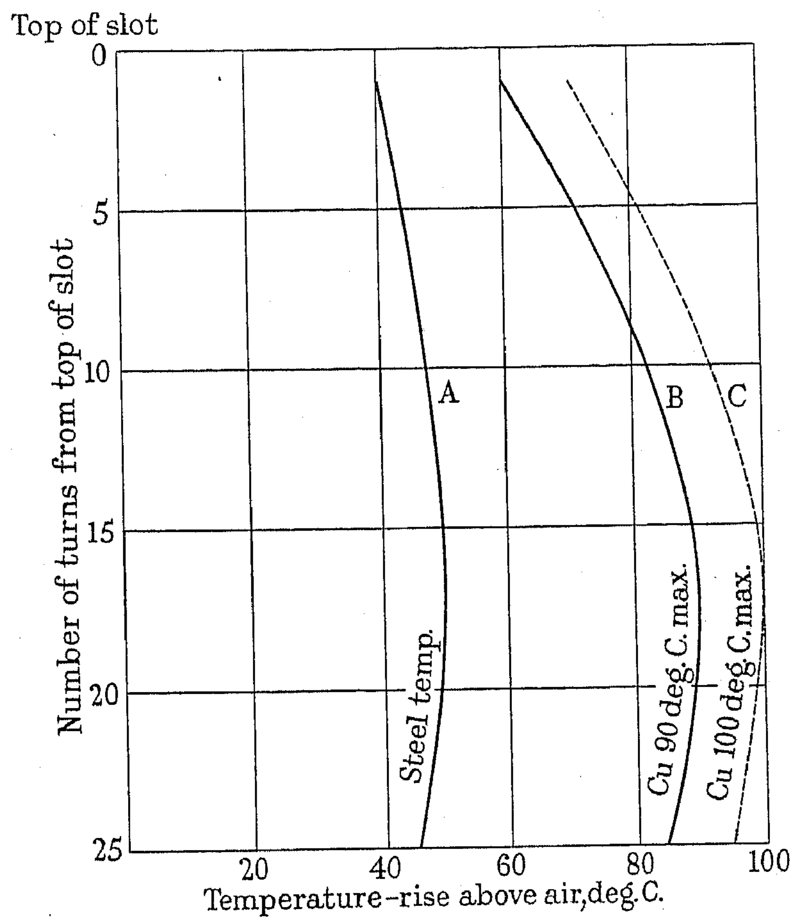


Fig. 1.—Curves showing temperature distribution at various depths of the slot.

The usual method of calculating the temperature-rise of the copper throughout the depth of the slot is based on the assumption that the thermal conductivity of the insulation is constant at all points through the depth of the slot. The introduction of an additional air space, however, has the effect of increasing the temperature-drop to a great extent and must therefore be taken into account in order to obtain the correct temperature distribution. As this additional air space only occurs over a portion of the depth of the slot, the effect is a material change of the temperature difference between copper and iron over a certain portion of the slot depth.

Fig. 1 shows estimated curves of the temperature difference at different depths of the slot. Curve A indi-

cates the temperature-rise of the tooth above the cooling air. The maximum temperature occurs approximately two-thirds down the tooth. The slight drop in temperature from this point to the root of the tooth is due to the fact that a portion of the heat transmitted into the tooth from the winding is taken away by the air flowing through ventilating ducts provided below the slot carrying the copper.

Curve B indicates the temperature of the copper, taking into account the temperature-drop through the insulation and making allowance for a maximum air space equal to the building clearance.

It is only in the lower portion of the slot that allowance has been made for the existence of air space and it is clear that the actual shape of the curve must necessarily be approximate, but it serves to indicate that the maximum temperature difference is greater than would be obtained by assuming constant heat-drop through the insulation. Moreover, the exact shape is not of great importance, as will be appreciated later. It is the maximum temperature difference which is of importance.

Now if copper is restrained from expanding due to temperature it will at first contract elastically until the compressive stress exceeds the yield point of the material, when permanent deformation will occur.

Stress/strain curves were taken on material in the condition in which it was used, and Fig. 2 shows a typical result. The temperature-rise of the copper has been added in order to show the relationship between temperature-rise and stress, when the copper is prevented from expanding.

As has already been pointed out, it is the differential expansion between the copper and the steel rotor which is of importance from the point of view of deformation of the copper. In order to illustrate the effect of the temperature difference between copper and steel, curves were made showing the stress in the copper and the contraction of the copper resulting from varying numbers of heat cycles, i.e. the number of times the machine has been started and stopped. These curves are shown in Figs. 3, 4, and 5, and are based on a temperature-rise of 50 deg. C. for the steel of the rotor body, and 90 deg. C., 95 deg. C., and 100 deg. C., for the copper. Under the temperature conditions shown in Fig. 3 the stress due to expansion in the copper would reach a value of 15 000 lb./sq. in. if the material was perfectly elastic, as in such a case the stress would increase along the line OA until it intersected the horizontal line at 15 000 lb./sq. in. It should be pointed out that, although this stress does not occur, use is made of it in constructing the diagram of the actual stresses and strains resulting after varying number of heat cycles, as it provides an easy graphical way of showing at a glance how far the contraction is likely to go on. It will be seen that this stress is higher than the copper is able to support, and a permanent deformation therefore takes place. The actual stress in the copper will be obtained by drawing a vertical line from point A until it cuts the stress/strain curve at A_1. The stress which the copper is able to support at this point of the stress/strain curve is equal to 11 400 lb./sq. in., and equilibrium is then established. This condition will continue so long as the machine is kept running. When the machine is shut down the copper will cool and, being free, will contract along the line A_1A_2. The amount of contraction which has occurred per inch is shown by OA_2. It should be pointed out that no change in length can take place until the speed has fallen to a value where the force holding the copper is less than the contraction force. When this

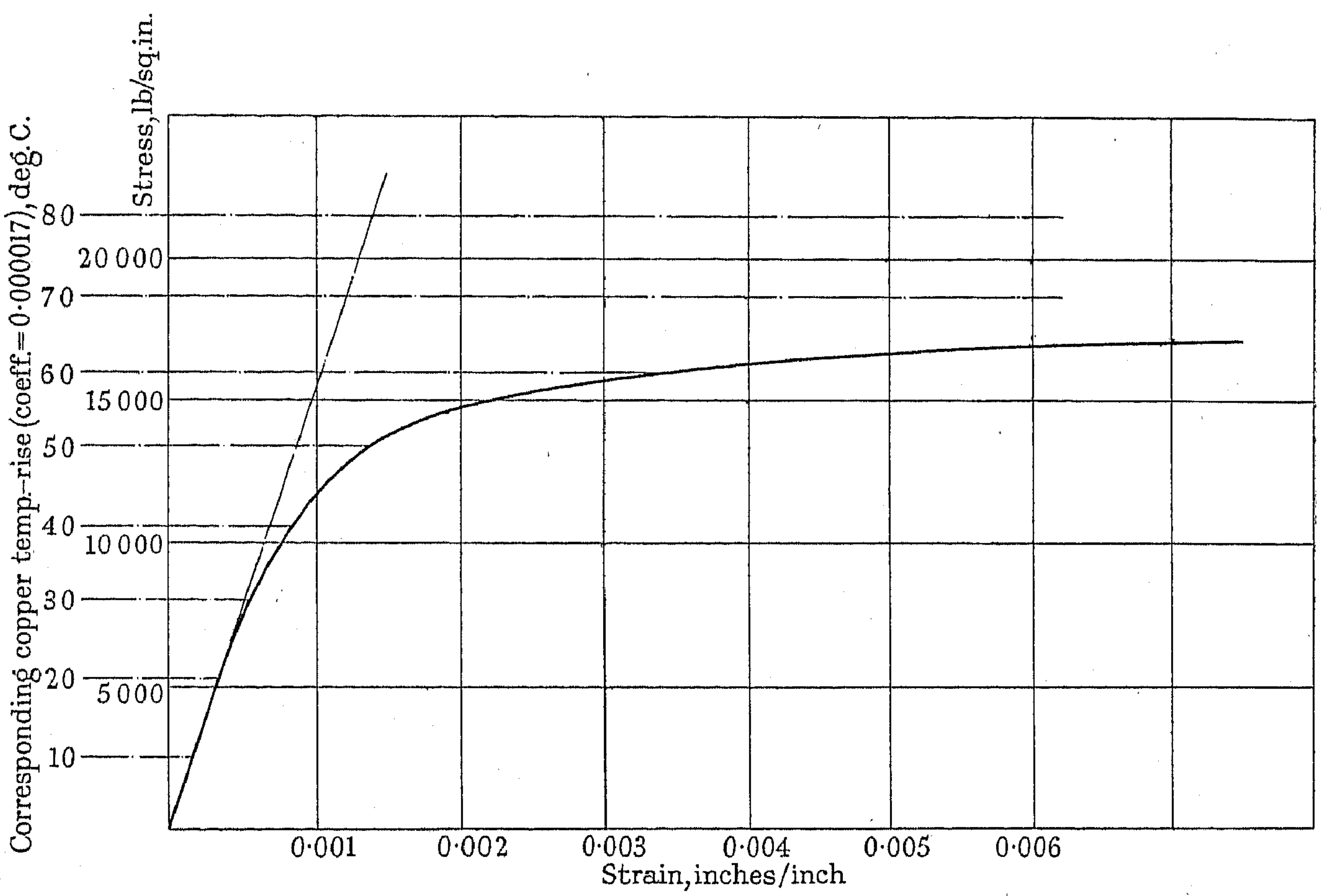


Fig. 2.—Load-extension curve for soft copper, and relation between stress and copper temperature-rise.

point is reached there will be a slip and the copper will then immediately contract. The point at which slip will occur depends on the temperature distribution along the depth of the slot.

of line BB_1 with the stress/strain curve at point B_1, where equilibrium is again established. It is of interest to note that the stress which the copper can now support is higher than was the case at point A_1. This is, of course,

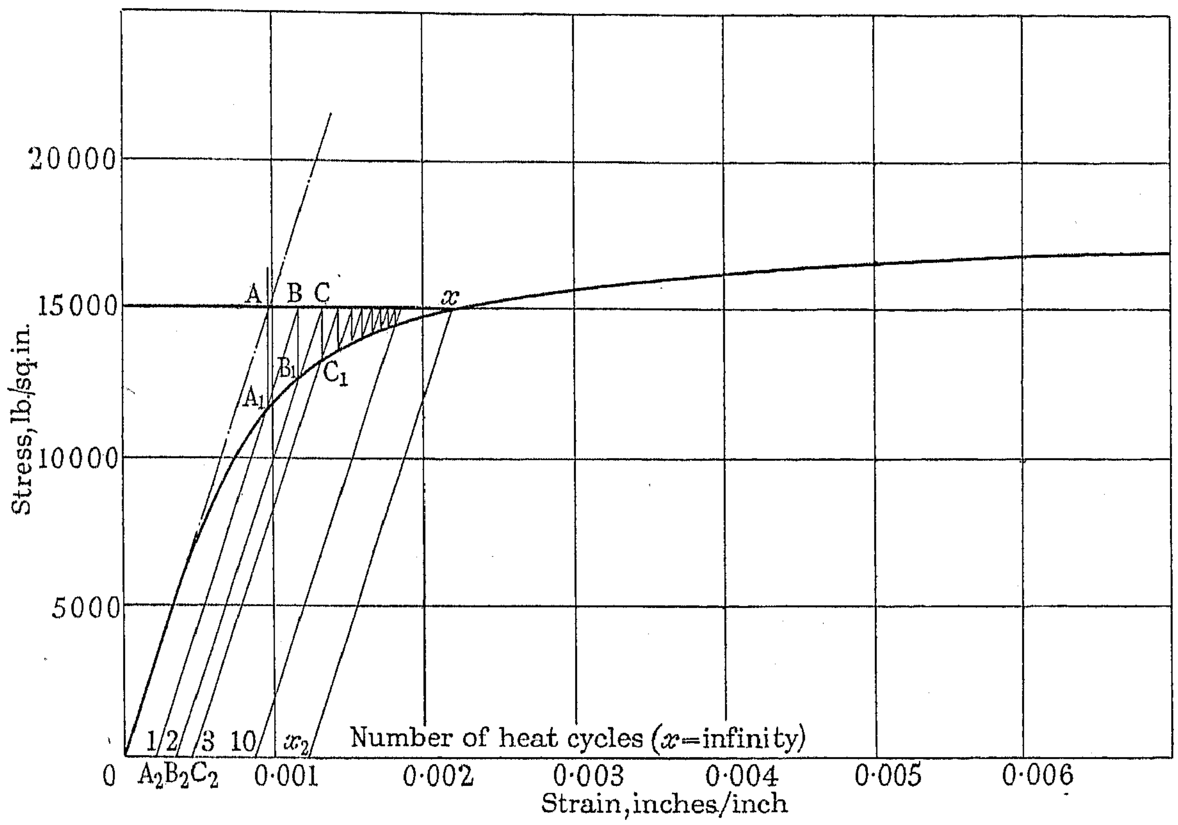


Fig. 3.—Diagram showing amount of contraction of winding, due to temperature-rise.

Copper temperature-rise = 90 deg. C.
Steel temperature-rise = 50 deg. C.

Coefficient of expansion of copper = 0·000017.
Coefficient of expansion of steel = 0·0000115.

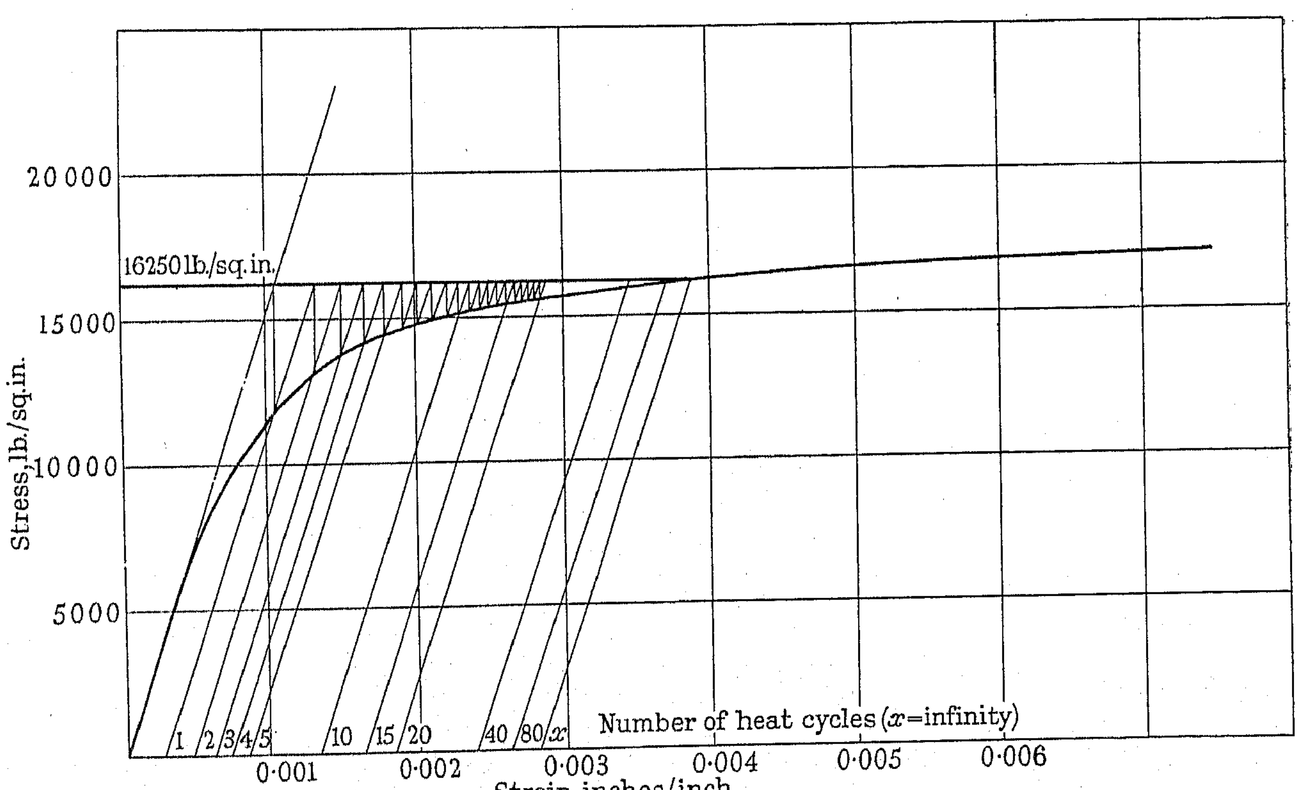


Fig. 4.—Diagram showing amount of contraction of winding, due to temperature-rise.

Copper temperature-rise = 95 deg. C.
Steel temperature-rise = 50 deg. C.

Coefficient of expansion of copper = 0·000017.
Coefficient of expansion of steel = 0·0000115.

The next time the machine is started the stress would tend to rise along the line A_2B until it reached the 15000-lb./sq. in. stress line. The actual stress is obtained in the same way as before and is given by the intersection

well known and is due to hardening of the material. On shutting down, contraction takes place along the line B_1B_2 and a further shortening results. For each successive starting and stopping this action will be repeated,

but it will be seen that the shortening is reduced for each successive start until at the point "x" the state has been reached when the copper is able to support the full stress of 15 000 lb./sq. in. imposed upon it and no further shortening will occur. When this point has been reached the heating and cooling cycles will follow the line x_2x.

Theoretically, an infinite number of heat cycles would be necessary before the contraction ceases, but practically the action stops after a comparatively few cycles as the amount of contraction becomes insignificant. The total reduction per inch is, as will be seen, in this case 0·00125 in. The total reduction over the whole length of the rotor will of course depend on the peripheral speed and the friction coefficient, as these factors control the percentage of the total length which is held sufficiently to prevent movement.

Figs. 4 and 5 have been drawn in order to show the effect of the temperature on the amount of contraction which takes place. Fig. 4 is drawn for the conditions where the temperature-rise of the copper is 95 deg. C., and that of the steel body 50 deg. C., as before. In this case the stress in the copper would tend to rise to 16 250 lb./sq. in., but again, as the copper cannot support this stress, shortening takes place until equilibrium is reached.

The total reduction per inch length which occurs under these conditions is 0·0028 in. or about 2·25 times the amount with 90 deg. C. temperature-rise of the copper.

Fig. 5 has been drawn for a temperature-rise of 100 deg. C. on the copper, the steel having a rise of 50 deg. C. as before. For these conditions the stress would tend to rise to 17 550 lb./sq. in., and in consequence the shortening is still greater. In this case the reduction in length will go on almost indefinitely, owing to the fact that the stress which the copper has to support, i.e. 17 550 lb./sq. in., is higher than the maximum indicated by the stress/strain curve.

It will be appreciated that the amount of contraction for each heat cycle will be very small after a large number of cycles of starting and stopping, as the horizontal line indicating the expansion stress then approaches the stress/strain curve.

It is of interest to note that after 80 heat cycles the contraction in this case is 0·006 in. per inch.

Fig. 6 gives a comparison of the contraction obtained from Figs. 3, 4, and 5. The point to be noted is the very large increase in the contraction for a very small increase in the copper temperature-rise. For an increase of only 10 deg. C., i.e. from 90° C. to 100° C., the amount of contraction will be several times as great. From this it will be clear that the temperature-rise is very critical and it will be appreciated that a comparative small change in the stress/strain curve will affect the amount of contraction to a very great extent.

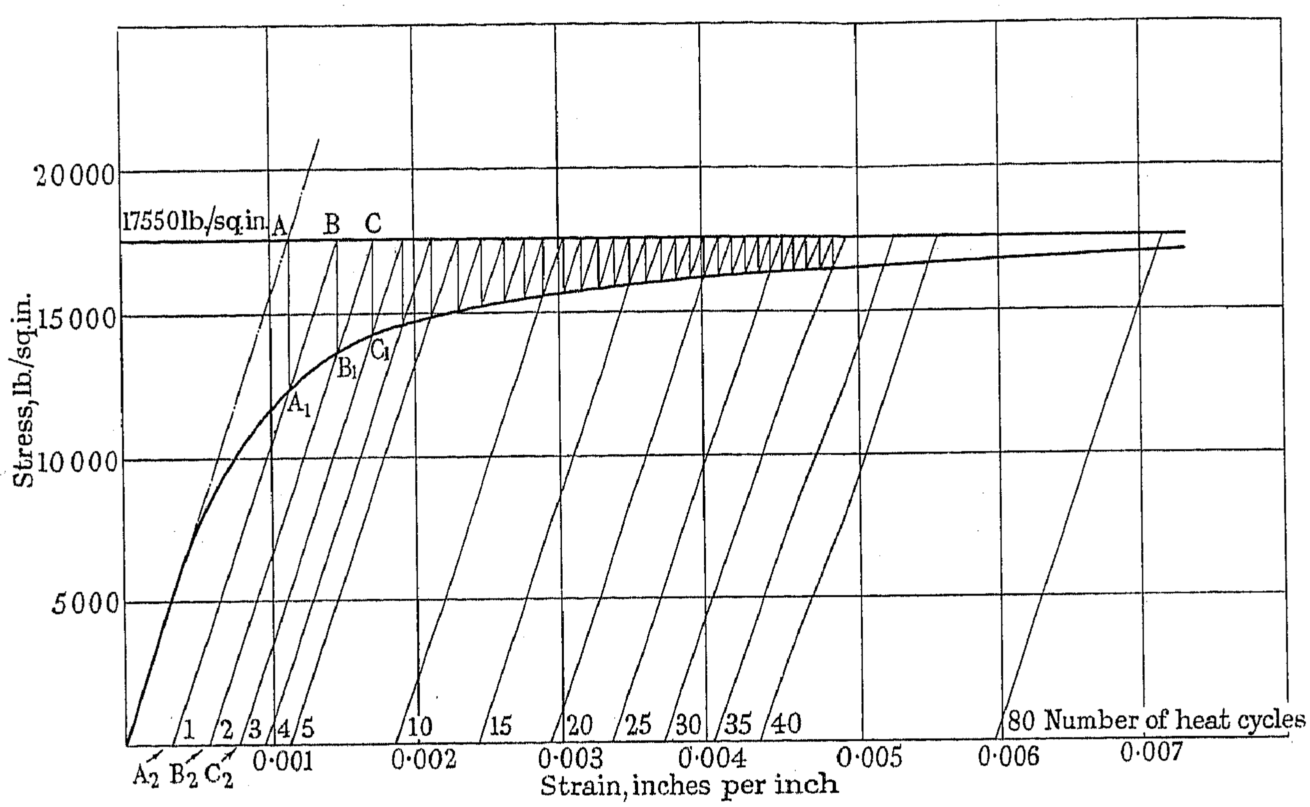


Fig. 5.—Diagram showing amount of contraction of winding, due to temperature-rise.

Copper temperature-rise = 100 deg. C.
Steel temperature-rise = 50 deg. C.

Coefficient of expansion of copper = 0·000017.
Coefficient of expansion of steel = 0·0000115.

So far we have considered the contraction per inch for various temperature conditions. The total deformation over the whole length of the rotor is, however, of most importance. As has already been shown, the temperature-rise affects the amount of contraction per inch very greatly; in fact it is almost critical in so far that at low temperatures the contraction for even an infinite number of heat cycles is negligible.

The temperature-rise also affects the length of conductor which is prevented from expanding, for it is clear that the expansion force acting on the copper is greater if the temperature-rise is higher. The restraining force per inch length of conductor is constant for a given peripheral speed and coefficient of friction, and for this reason the length of conductor (counting from the end of the rotor) which can expand is greater, and the portion of the conductor which is prevented from expanding is smaller the higher the temperature-rise.

Fig. 7 shows the conditions of top and bottom con-

ductor and also the 18th conductor, which has the maximum temperature-rise. The length of the rotor body was 160 in. These curves are based on a maximum

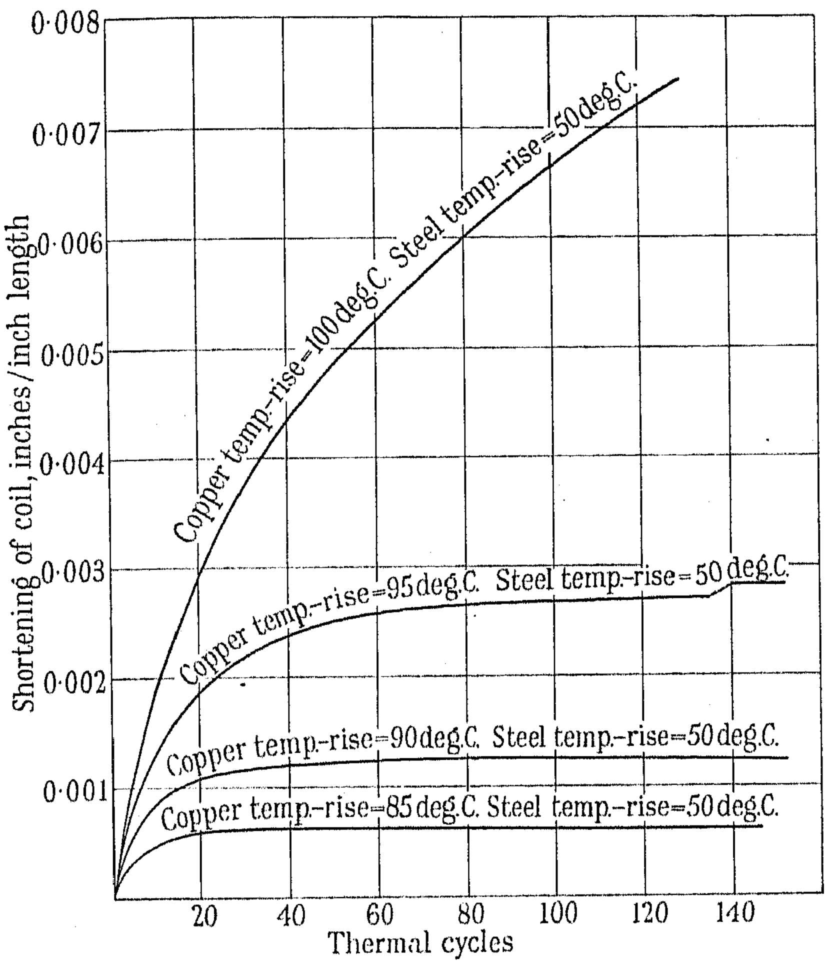


Fig. 6.—Curves showing amount of contraction for varying number of heat cycles and temperature-rise.

Coefficient of expansion of copper = 0·000017.
Coefficient of expansion of steel = 0·0000115.

temperature-rise of 95 deg. C. on the conductor, and the friction coefficient has been taken as 0·3. From these curves it is simple to compute the contraction of the copper throughout the depth of the slot, and the result is shown in Fig. 8. The total contraction obtained is, as will be seen, 0·25 in. for the conductor subjected to maximum temperature and is negligible for the top conductor.

The actual maximum deformation was considerably more than the calculated value in some coils, and varied very considerably for different coils. Some coils showed no shortening at all. The calculated results agree with the actual condition in that the maximum contraction had occurred towards the bottom of the slot: no shortening had occurred of the top conductor. This result was at first very baffling, as it was clear from the outset that a greater portion of the turns at the top of the slot would be restrained from expanding than would be the case for the turns situated at the bottom of the slot. This apparent paradox is explained by the marked influence of temperature on this phenomenon. Due to the lower stress in the top conductor practically the whole of the strain is elastic and the plastic deformation is negligible.

It must be appreciated that, owing to the complicated nature of the problem, it is not to be expected that calculations would give accurate results in magnitude, as comparatively small changes in temperature affect the result to a marked degree.

Referring to the question of temperature-rise, it should be noted that the increase in temperature which is of importance in connection with this problem is not that which is measured at the end of a run as this would be obtained by deducting from the total temperature of the copper the inlet air temperature existing at the time of shutting-down.

The temperature-rise affecting the expansion and contraction of the copper is that obtained by deducting the temperature of the copper at starting from the final temperature.

This may make a difference of several degrees in cases where high cooling-water temperatures exist. It is also of importance that coolers should not be allowed to get dirty as this increases the temperature of the inlet air and, therefore, also the temperature-rise of the copper above the air at starting.

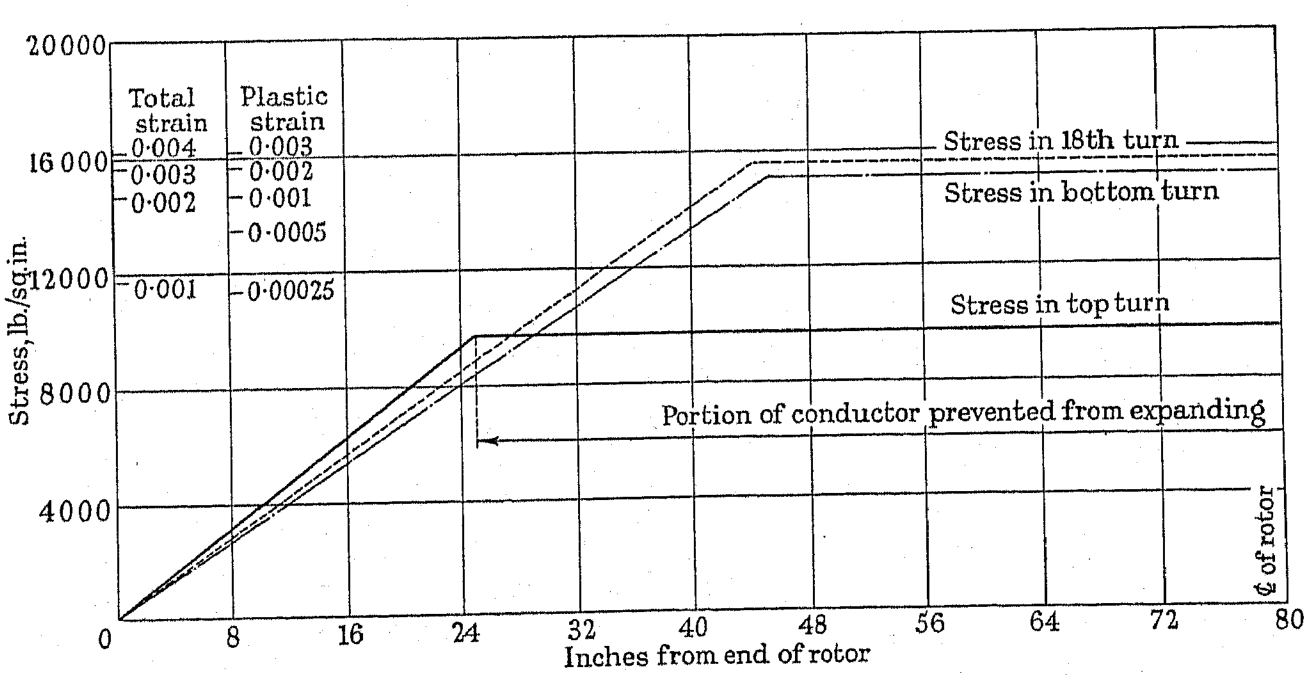


Fig. 7

Overloads

As has been shown, the limits of temperatures at which the contraction is negligible and that at which trouble may be expected are very narrow, and for this reason the author would draw attention to the importance of not allowing machines to carry overloads beyond the maximum for which they have been built. Such practice is not infrequent as it is usually considered safe to overload machines for short periods which would not materially affect the life of the insulation.

The effect of overloading on the phenomenon under consideration is, however, so marked that before overloads are allowed special consideration is necessary in order to avoid ill-effects due to possible deformation of the copper. In order to illustrate this point a calculation has been made of the possible amount of contraction which may occur on a machine subject to overloads of 10 % only.

Consider a machine designed for a maximum continuous rating and a temperature-rise on the rotor of 80 deg. C. by resistance. It has been shown that the maximum hot-spot temperature may be about 95° C. in certain portions of the slot; this is perfectly safe so far as the insulation is concerned. The temperature-rise of the rotor body would be about 50 deg. C.; with 110 % load the maximum copper temperature would be 114° C. and that of the rotor body about 55° C. The stress in the copper under this condition would tend to rise to just over 20 000 lb./sq. in., with the result that the contraction at the beginning would be approximately 0·0005 in. per inch length of the portion of the conductor restrained from moving.

After only 20 heat cycles the contraction would be 0·0127 in. per inch and the total shortening would be 0·38 in. This amount is 2·3 times that which would take place for the same number of heat cycles with the machine operating under its specified rating at which the shortening would have been negligible.

After 80 heat cycles the total contraction would be 0·83 in., or three times the total contraction after an infinite number of heat cycles at normal maximum continuous rating. It is to be noted that contraction will not stop after 80 heat cycles under overload conditions, so that the final amount of contraction will be still greater.

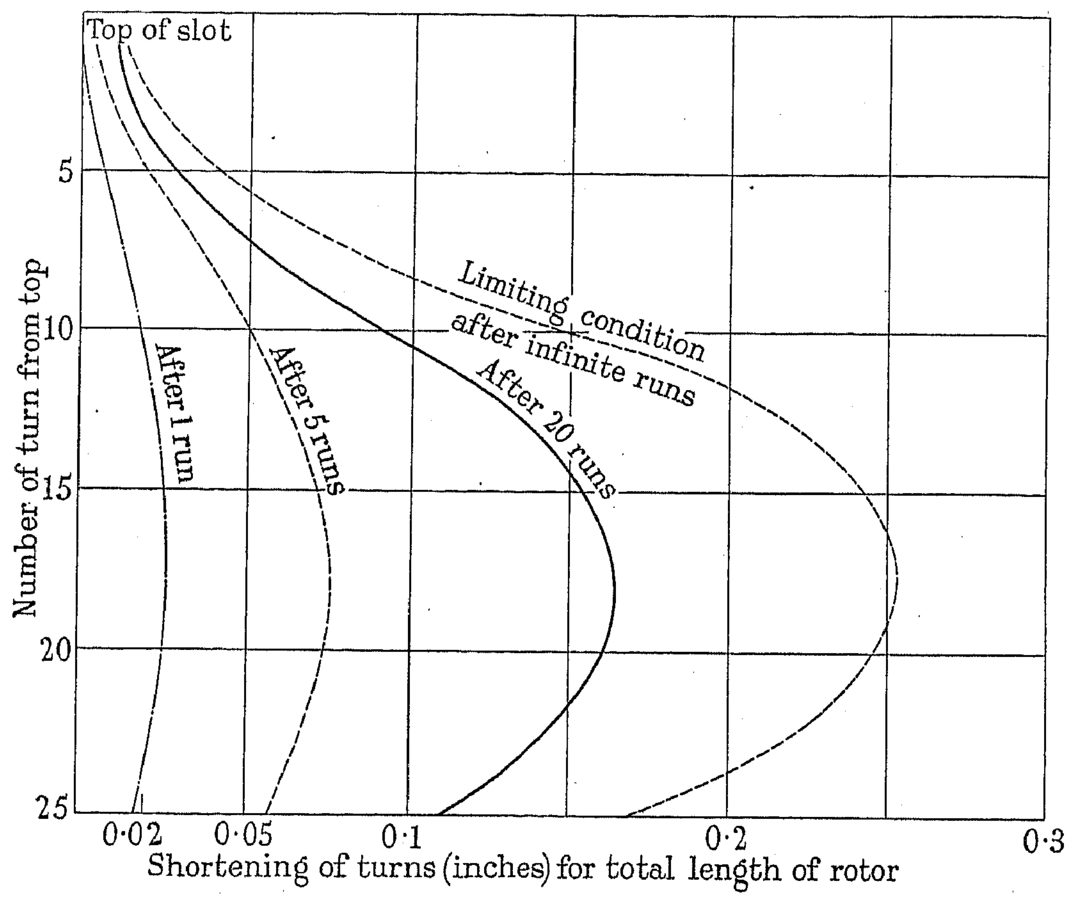


Fig. 8.—Curves showing total shortening of coil.

	Top of slot	*Max.*	*Bottom of slot*
Copper temperature-rise, deg. C.	65	95	90
Steel temperature-rise, deg. C.	40	50	45

Methods of obviating the trouble

The existing methods of design and manufacture have been evolved over a number of years and it is interesting to note that exactly the same construction and methods of supporting the coils have been in use since 1926 with eminently satisfactory results. Indeed, duplicate machines to that which has shown this trouble have been in operation since 1932 without any trouble whatsoever, and this serves to emphasize the fact that the small variations which occur in different machines and, in addition, differences in loading as well as difference between the air temperature of the station and actual inlet air to the machines, have caused the trouble to appear.

Hard-drawn copper has, as is well known, a much higher elastic limit and the expansion stresses would therefore be within the elastic limit so that no permanent deformation would occur with this material. The use of hard copper has already been suggested.* Such a change

* *Electric Journal*, 1936, vol. 33, p. 262.

will involve careful considerations of technique in manufacture, and experimental work has shown that it is possible to employ hard-drawn copper for rotors of this type. Machines are being built with the slot portion of the coils, up to 6 in. from each end, in hard condition. From this point the copper is annealed as this is necessary for manufacturing reasons. This method is, however, not the only one which offers a satisfactory solution.

The alternative is, of course, to provide means to limit the contraction of the copper. This can be done by additional blocking supporting the ends of the coils, and it may be of interest to consider what happens under these conditions. Consider the case where the coil ends are supported rigidly in position. The stress conditions by the intersection of line 1B with a line from AB drawn from A at right angles to OA.

The stress at point B is still higher than the copper can support and the copper contracts, causing the stress to fall to B_1. Upon cooling the stress falls along B_1B_2 and the copper is now subjected to a tensile stress slightly higher than that after the first run. This increase is, of course, due to the additional contraction which took place during the second heat cycle. A similar action takes place during each subsequent heat cycle, but the contraction becomes negligible after the first two or three heat runs.

Theoretically an infinite number of heat cycles would be required before the contraction became zero, but

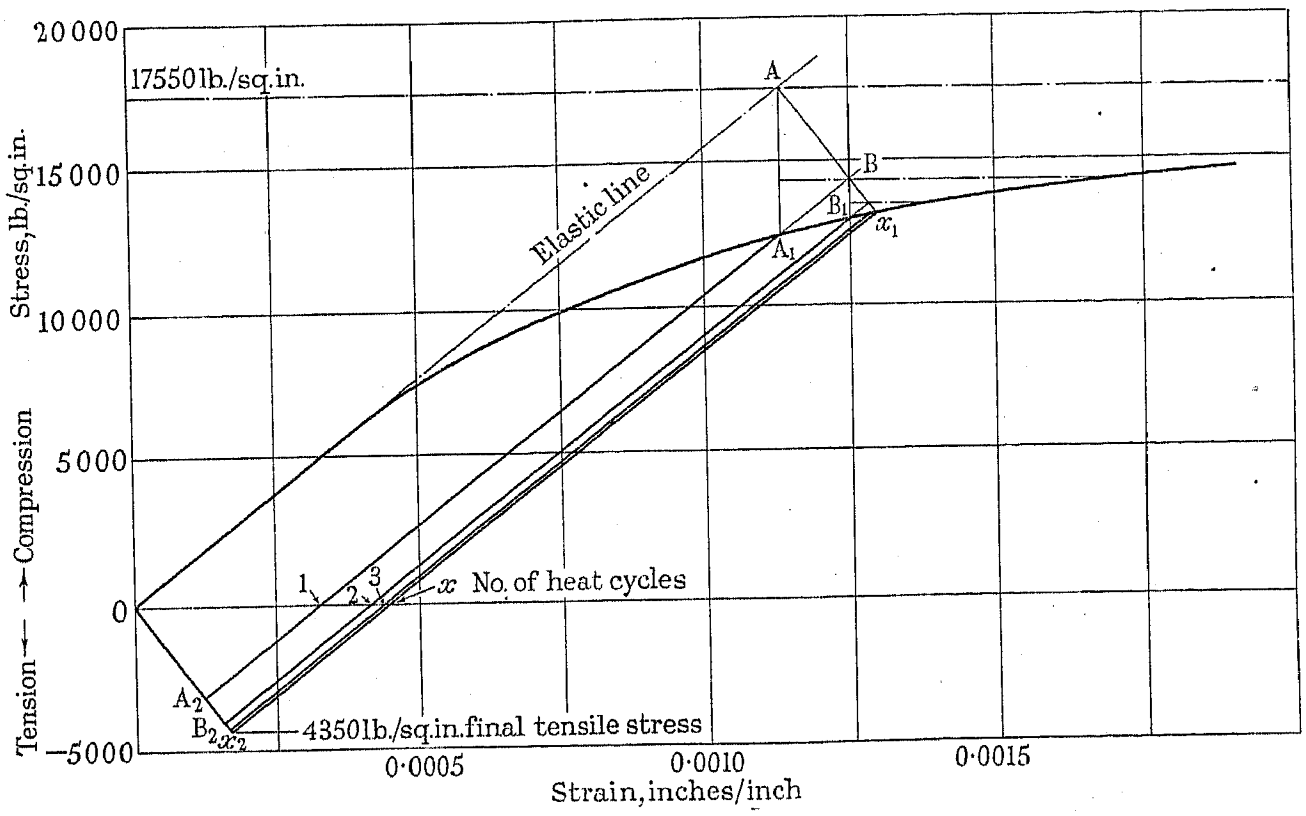


Fig. 9.—Diagram showing amount of contraction of winding due, to temperature-rise. Coils held rigidly at ends of rotor when cooling.

Copper temperature-rise = 100 deg. C.
Steel temperature-rise = 50 deg. C.

will then be as shown in Fig. 9. The conditions assumed are:—

Temperature-rise of copper, 100 deg. C.
Temperature-rise of steel, 50 deg. C.

The contraction stress in the copper would tend to rise along line OA up to 17 550 lb./sq. in., but owing to contraction it falls along line AA_1 until this line intersects the stress/strain curve at A_1.

When the rotor cools the stress falls along line A_1A_2 until at point A_2 it intersects a line OX_2 drawn from O at right angles to OA_1. The copper is then under a tensile stress as it is held at each end and prevented from contracting.

The amount of tensile stress is given by the line $1A_2$ and is well within the elastic limit. When the machine is run up again the effect of the temperature-rise is first to release this tension, after which the compressive stress increases along the line 1B. The point B is obtained practically the stress would follow line x_1x_2 after comparatively few heat cycles. The final tensile stress in the copper is also well within the elastic limit.

It will, of course, be appreciated that it is not possible to fix the ends of the coils absolutely rigidly, and this case is given in order to show that even with rigidly-held coil ends some permanent contraction of the winding occurs, although negligible for practical purposes. Intermediate conditions where the coil ends are held with a certain amount of flexibility can, of course, be worked out, in which case the resulting tensile stress in the copper would be less than for the case of rigid supporting. Under such conditions the shortening would of course, be greater, but could be kept within satisfactory limits.

It should be pointed out that hard-drawn copper anneals slowly if subjected to temperatures much lower than the usual annealing temperature. Investigations on this point show that complete annealing will occur after approximately 35 000 hours if hard-drawn copper

*

is subjected to a temperature of 140° C. This time is, of course, well within the life of a machine, but it must be appreciated that even hard-drawn copper is subject to limitations from a temperature point of view.

It has been suggested that by modifying the method of starting-up a machine it would be possible to prevent shortening of the copper, and it may therefore be of interest to review different procedures.

Case 1.

(*a*) Run up to speed.
(*b*) Heat up.
(*c*) Run down to zero speed.
(*d*) Cool down.

Result: Coils may shorten.

Case 2.

(*a*) Run up to speed.
(*b*) Heat up.
(*c*) Cool down.
(*d*) Run down to zero speed.

Result: Coils may shorten.

Case 3.

(*a*) Heat up to one-half normal temperature-rise standing, or at very low speed. Copper has then expanded half the total amount.
(*b*) Run up to speed.
(*c*) Heat up to full temperature-rise. Copper will then expand to full amount, but the strain will be elastic as temperature-rise after the coils are held will only cause a stress within the elastic limit.
(*d*) Run down to zero speed.
(*e*) Cool down.

Result: No change in length.

Case 4.

(*a*) Heat up to half normal temperature-rise standing, or at very low speed.
(*b*) Run up to speed.
(*c*) Heat up to full temperature-rise.
(*d*) Cool down to half temperature-rise.
(*e*) Run down to zero speed.
(*f*) Cool down.

Result: No change in length.

Case 5.

(*a*) Heat up to full temperature-rise standing, or at very low speed. Copper will then expand to the full extent.
(*b*) Run up to speed.
(*c*) Cool down. When cooling down at speed the copper wants to contract but, being held, cannot do so and will therefore be stretched if temperature-rise is high enough to cause a stress beyond elastic limit.
(*d*) Run down to zero speed.

Result: Coils may lengthen.

Case 6.

(*a*) Heat up to full temperature-rise standing, or at very low speed.
(*b*) Run up to speed.
(*c*) Run down to zero speed.
(*d*) Cool down.

Result: No change in length.

Case 7.

(*a*) Run up to speed.
(*b*) Heat up.
(*c*) Run down rapidly to a speed at which the copper will be released; this will then expand.
(*d*) Run up to speed again immediately, when copper will be held in position.
(*e*) Cool down. Copper will then want to contract but on the held portion it cannot do so and will therefore be stretched and any plastic deformation caused during heating will be removed.
(*f*) Run down to zero speed.

Result: No change in length.

Of the various methods of starting-up and shutting-down differing from normal operation practice, the one in Case 3 is the only practicable one and can be carried out without any serious difficulty as half normal temperature-rise can usually be obtained. It should be noted that any preheating, even if the temperature-rise is below half normal, will be of advantage as it reduces the amount of shortening.

The author wishes to acknowledge valuable suggestions from Dr. Bernhard Price in investigating this problem.

INSTITUTION RECOLLECTIONS

By Ll. B. ATKINSON, Past-President.

(*Address* delivered at the* CONVERSAZIONE OF OVERSEAS MEMBERS, 13*th June*, 1939.)

On the occasion of the Conversazione of overseas members it is the custom of the Council to arrange for a lecture likely to be of interest to such members. On the present occasion, and having in mind the fact that most overseas members may broadly be classed as of the present generation, it is thought that a short account of the early days of this Institution and of those who founded and built it up in the last generation may be of interest. The Council have selected me for the task, as one of the comparatively few now remaining who personally know of those early days. I do not propose to go closely into the history of The Institution, for the Council recently asked Mr. Rollo Appleyard to write a "History of The Institution" and it will be published this autumn—I should like here to acknowledge my indebtedness to this book, a proof of which I have been allowed to see, for some of the facts and dates included in what follows. I want rather to focus your minds on those high spots or major steps in the early days of The Institution which went to build up our science and industry, with some personal recollections of the men who stood in the forefront.

As you doubtless know, this Institution began as The Society of Telegraph Engineers, founded in 1871 by men interested in telegraphy by land and under sea—principally by men in the service of the great telegraph companies, or of the British land-telegraph service which had been transferred to the State in 1870, or of the manufacturers supplying their apparatus, or of men in the Royal Engineers who were applying electric signalling to the purposes of field armies. There had been earlier one or two attempts to found an electrical society, but they had not succeeded, and, indeed, it was time that there should be a society to discuss the technique of electrical communications when it is noted that by 1871 there was about £30 million of capital involved in these services.

The first president was Dr. C. W. Siemens, later Sir William Siemens, to whom I shall refer again, and up to 1875 the proceedings were entirely devoted to subjects of importance to telegraphy. But in 1876 came the first great awakening, the invention of the electromagnetic telephone by Alexander Graham Bell, which instrument he himself described to the Society at a Special Meeting held in 1877. His only other appearance at The Institution was in 1891 when he was in London and, at my invitation, attended a meeting and spoke a few words. It is difficult now to realize the excitement this invention stirred up in the electrical world, followed as it was in 1877 by the announcement of the Edison carbon transmitter.

In February, 1878, Mr. W. H. Preece (afterwards Sir William Preece) exhibited to the Society an Edison phonograph, which he stated was the second instrument only that Edison had constructed, the voice being recorded on a sheet of tinfoil which was then used to reproduce the words spoken to it. In the same year Dr. Siemens again occupied the chair, and in his Address, which dealt largely with technical and other matters connected with land and deep-sea cables, he went on to review the gradual awakening of engineers and others to the importance of electric lighting, already, as he showed, adopted in France for lighthouses. He proceeded to give some interesting facts and figures relative to electrical transmission of power.

In the same year (1878) the then Acting Secretary of the Society placed before it a Report on what he termed "a new form of electric light," in which he described the Jablochkov candle, two strips of carbon separated by kaolin which, at the arc temperature, became a semi-conductor contributing to the brightness and steadiness of the light by becoming highly incandescent. This candle did away with the necessity for regulating mechanism and was, indeed, the first commercial form of electric light. And so in a period of about 18 months the Society and the public had spread before them the beginning of the telephone, the phonograph, electric lighting, and electric power transmission.

In 1878 an International Exhibition had been held in Paris, in which a great deal of electrical apparatus was shown, but it was not collected together and, but for a very interesting Report presented to the Society by Major-General Webber, would have attracted little attention from electrical engineers.

In May, 1878, Professor Hughes described to the Royal Society his invention or discovery of the microphone, and later made a communication to the Physical Society on the physical action of the microphone, but he made no announcement on this subject to the Society of Telegraph Engineers, though in a discussion on papers by Messrs. Bidwell and Munro in 1883 before the Society he contributed much interesting information arising from his researches.

Returning for a moment to topics relating to electric generation, the self-exciting direct-current dynamo was described almost simultaneously at the end of 1866 and the beginning of 1867 by Wilde and Wheatstone in this country and by Werner Siemens in Germany. Although Wheatstone had described what we now call a shunt-wound dynamo, practically all dynamos at that date were series-wound, a method which was suitable for running arc lamps in series with a constant current. In March, 1880, however, Alexander Siemens read a paper before the Society on "Some Recent Improvements in Electric Light Apparatus," in which he described what he

* The Address was illustrated by lantern slides, portraits of the early pioneers, and pictures of early apparatus.

called a new method of exciting the magneto by a shunt circuit, as proposed originally by Prof. Wheatstone. There had been in that year an exhibition of electric light (arc lighting) in the Albert Hall, when it is recorded that the "unruly behaviour" of the electric light had greatly heartened gas shareholders, who earlier on had yielded to a panic, gas shares falling in a few weeks to less than half their value.

On the 24th November in this same year Joseph Wilson Swan (later Sir Joseph) read a paper before the Society on "The Subdivision of the Electric Light." At that time this was the great problem awaiting solution. Powerful light by the arc could be had; but could small lamps become possible? The first I heard of this must have been when I was about 14 years old, and I remember it as if it were yesterday. I passed in a cab with my father near Hyde Park Corner and he said "Lontin has succeeded in subdividing the electric light." At the above meeting, Swan made a public exhibition of carbon-filament vacuum lamps. His first lamp had carbonized-paper horseshoe strips. Those which I now show had a round elastic carbon wire, produced by squirting a viscous carbon compound, afterwards carbonized, an invention due, I believe, to Sir James Swinburne and on which the whole artificial-silk industry is based.

In 1880 at a Special General Meeting of the Society held at the time of the first Electrical Exhibition in the Palais d'Industrie, Paris, Dr. Werner Siemens read a paper in French in which he described electric traction experiments, with two rails acting as the return circuits, with a separate supply-rail; he also mentioned a suspended-car system fed from the suspending rail.

And so, by the end of 1881, the fundamentals were laid down on which electrical engineering was for a decade or more to move. The years following were devoted to rational designing, and to the questions of supply from a central station.

In 1884, Gisbert Kapp had published a formula for the electromotive force of a continuously-wound direct-current machine in terms of the number of revolutions of the machine, the number of turns on the windings, and the area of iron through the armature, all multiplied by an empirical constant depending on the type of machine. At that time the field-magnet windings were determined by putting test coils on to the magnet cores and running the machine with various currents through these coils, thereby settling the number of ampere-turns required.

Lord Kelvin had previously called the attention of Crompton to the fact that Maxwell in his treatise had shown that the integral magnetic force along any closed line threading a coil carrying a current was $0 \cdot 40 \times$ ampere-turns; but whilst this seemed to give a simple method of determining the magnetic flux along a line in a homogeneous medium, its application to a line along a mixed path of iron and air of various cross-sections was not apparent.

In 1885, Kapp read a paper before The Institution of Civil Engineers in which by empirical reasoning he compared this compound magnetic path with the problem of applying Ohm's law of electrical resistance to a circuit of various materials and sectional areas, the conductivity of each being known.

In such a case the electric current is calculated in a form in which the electric force is divided by the sum of the separate electric resistances, and so Kapp developed a form where the electromagnetic force was divided by the sum of what he called the magnetic resistances of the iron and air paths respectively, making allowance for the fact that there were magnetic leakages so that the magnetic force was not acting entirely along the path through the armature windings. In the discussion, Dr. John Hopkinson stated that he and his brother, Dr. Edward Hopkinson, had used a similar method two years previously.

For the purpose of the magnetization curve of iron Kapp used an empirical formula originally published by Frohlich, and in 1886 he followed this up by a paper to the Society under the title "The Predetermination of the Characteristic of Dynamos," in which he expanded the same subject. In the same year two communications were published in the *Journal* and *Philosophical Transactions of the Royal Society* by Drs. J. and E. Hopkinson, in which, introducing the actual magnetization curve of the iron used in a particular machine, they showed the magnetic force required for the several air and iron paths in the machine and, finally summing these, applied the Maxwell expression for the integral magnetic force. These papers, together with certain useful methods of approximation to the magnetic leakages given by Prof. George Forbes in the discussion on Kapp's paper, solved the question of the predetermination of the characteristic curve of a direct-current dynamo.

It will have been observed that several of the important papers I have referred to were published in the *Proceedings* of The Institution of Civil Engineers, the Royal Society, the Royal Society of Arts, etc., and it may be necessary to explain this. The reason lay in the fact that the Society was still looked upon as The Society of Telegraph Engineers. The Institution of Civil Engineers claimed that the new art of heavy electrical engineering was one branch of civil engineering as opposed to military engineering, and that Institution was taking effective steps to attract papers and discussions on the new science, this being reinforced by the fact that many of the pioneer engineers had been members of The Institution of Civil Engineers before they joined The Society of Telegraph Engineers.

Alternating-current supply, and the problems connected therewith, now largely occupied the stage. The Siemens alternating-current dynamo with a ring of magnets of alternating N and S polarity facing one another across the air gap, with a ring of coils having no iron cores revolving in the space between them, was largely used. Experiment had shown that these machines would not run in parallel unless mechanically coupled; and so much was this the belief that in 1886–1887, when Ferranti had designed and was building the first large-scale alternating-current central station at Deptford, units comprising engines and dynamos of 10 000 h.p. were being built to obviate the difficulty. It is true that in 1884 Dr. John Hopkinson, in a paper before The Institution of Civil Engineers, had explained from theoretical considerations that alternating-current generators could be run in parallel if in the armature circuit there was a certain amount of self-induction; and that in co-operation with Prof. W. G. Adams he had proved

this experimentally at the South Foreland lighthouse installation with Holmes alternating-current magneto-generators. The best results, according to Hopkinson, would be obtained when the coefficient of self-induction multiplied by $2\pi T$ equals the resistance of the armatures and the connecting circuits.

In 1889, however, Mr. W. M. Mordey read a paper before The Institution on " Alternate-Current Working," in which he boldly challenged this idea and laid down the proposition that parallel working was best obtained with an armature circuit of negligible resistance and self-induction; and he gave information in his paper, and a demonstration to members of The Institution next day, which appeared strongly to support his claim. At all events, from that moment the parallel running of alternators became the practice, and the enormous Ferranti sets at Deptford designed to overcome this supposed difficulty were never completed.

I must go back one session to mention the subject of transformers. Those which in 1888 were in use on a considerable scale were built empirically, and designers were still groping for a rational method of designing a transformer for any given work, but in this session two papers were read, one by Kapp and one by Prof. G. Forbes, the former giving graphical and the latter analytical solutions of the problems of design, each taking the assumed magnetic flux in the iron core as the factor common to the primary and secondary electric circuits and working backwards and forwards from this, so enabling complete solutions to be reached.

In the discussions on this paper Prof. Ayrton put forward a proposal to give a constant or rising voltage on the secondary terminal by a compounding circuit, following the method of the compound winding of a dynamo. For the first time I, a youth then under 25, rose to speak in The Institution. I referred to Ayrton's remarks (I had not long before sat under him as a student), and said: " He admits that he has not gone fully into the question. I have devoted some time to its consideration, and have come to the conclusion that somewhere or other there is a fallacy in it. . . . I am inclined to think that compound winding of transformers cannot be done." It so happens that I was right.

Through 1889–1891 the battle of the systems, direct current with accumulators or alternating current with transformers, was then at its height. No question of technique ever raised such vehemence and bitterness. Crompton and Lord Kelvin the protagonists for the former; Preece, Mordey, Swinburne, Kapp, and Ferranti, leading the latter. The struggle had all the vehemence of religious fanaticism.

I will close this phase of the emergence of the electrical industry by reference to a paper by Crompton in 1891 on the cost of generating and distributing electricity, in which he for the first time introduced the conception of load factor; and to a paper by Prof. G. Forbes in 1893, on " The Electrical Transmission of Power from Niagara Falls." Forbes had fought, supported only by George Westinghouse, for alternating-current 2-phase transmission for this work, and had designed that type of vertical-shaft alternator later known as the umbrella type for this installation. Forty years later I saw this pioneer generator still in service in the power house at the Niagara Falls. It was 11 years later that the steam turbine was introduced to The Institution in a paper by Sir Charles Parsons, Gerald Stoney, and C. P. Martin.

Attention now passed from currents carried by conductors to currents and electrical actions in space. Sir Wm. Crookes was President in 1891 and his Address was on " Electricity in Transit from Plenum to Vacuum," a discourse illustrated by experiments of great novelty and beauty with striations, dark spaces, radiant matter, Edison effect, and the generation of matter, in fact the beginning of our knowledge of the electron and the electrical constitution of matter.

In the following year (1892) a Special Meeting of The Institution was held in the theatre of the Royal Institution, when Nikola Tesla, who had already become famous for the invention of the 2-phase alternating-current motor, gave a remarkable experimental lecture on " Experiments with Currents of High Potential and High Frequency." He was, indeed, showing us, though it was not then recognized, how energy could be transmitted by high-frequency electromagnetic oscillations.

In 1898 Sir Oliver Lodge read a paper on " Improvements in Magnetic Space Telegraphy " and Mr. Sydney Evershed on " Telegraphy by Magnetic Induction," the beginnings of wireless signalling, and both papers stressed the importance in one way or another of syntony or, as we now say, resonance between transmitter and receiver.

Excitement had been stirred up by the lay Press on what was being done by Marconi and the British Post Office under Preece in the way of wireless signalling; and when in 1899 Marconi described his system to The Institution he referred also to syntonic reception. So many members were unable to get into the lecture hall to hear his Address that an additional Special Meeting was held in the Exeter Hall, when Marconi repeated his Address. Thus, in a period of less than 30 years, all the great fundamentals had been opened up and expounded and discussed in The Society of Telegraph Engineers, which, founded in 1871, in 1880 became The Society of Telegraph Engineers and of Electricians, in 1883 was incorporated under the Companies Acts, in 1888 became The Institution of Electrical Engineers, and in 1921 was granted a Royal Charter by King George V, who also became its Patron. The Institution had from its inception held its meetings at The Institution of Civil Engineers, but in 1910 it acquired the present building. In this building, early in 1911, Dr. Kennelly gave a series of lectures on " The Application of Hyperbolic Functions to Electrical Calculations," and it is interesting to note that this electrical engineer of world-wide repute and an Honorary Member of The Institution commenced his electrical career as a clerk in the office of The Institution at a salary of £1 per week.

If one reads the papers and discussions thereon of the early days one is struck by the fact that very few men took part in this work, and the same men contributed to nearly all the discussions. So much was this the case that a group of the younger men memorialized the Council on the fact that so much time was occupied by contributions by elder, and mostly Council, members that the younger members had no opportunity of expressing their views.

Thinking over the men whom I remember as being in the forefront of this Institution in educating one another and the world in the possibilities and achievement of electrical science, I can count up a couple of dozen. It is an invidious task to pick out a few from these, but the time at my disposal makes this a necessity.

The first President (1872) was Dr. C. W. Siemens, an old friend of my father, one of a very gifted family, all of them pioneers—either individually or together—in telegraphic and signalling applications of electricity, in the early days of electric lighting and power and railways and in industrial banking, and Dr. Siemens especially as a metallurgist, who made basic steel production a possibility. He was a clever business man, and was stated to have made three fortunes: one of these he spent on experiments, etc., one he lost in the Landore steel works, and one he kept. I had the great advantage that he mapped out my engineering training, with the idea that I should become a personal technical assistant, but his death in 1883 put an end to that idea.

Sir William Thomson (Baron Kelvin), again a member of a very remarkable family, was President in 1874. At 21 years of age he was Second Wrangler and Smith's Prizeman at Cambridge; electrician to the Atlantic Cable Co. from 1857 onwards until the final success; inventor of the siphon recorder, the modern marine compass, and other important nautical instruments; Professor of Natural Philosophy and subsequently Chancellor of Glasgow University; during the period 1846 to 1899 (53 years) a prolific discoverer in the science of thermo-dynamics as well as in electrical science. To him largely we owe the electrical units of measurement, the early definition of which contributed very greatly to the rapid advance of electrical science. To hear him speak on any of these subjects was a delight, and an education in clear thinking and lucid exposition.

Sir William Henry Preece was President in 1880. His earlier engagements with various telegraph companies led to his transfer in 1870 to the British Post Office, where he subsequently became Engineer-in-Chief and Electrician. He had an unbounded enthusiasm for the new inventions and discoveries of the late seventies and eighties; he was a splendid popularizer of these things, and was always ready to assist the younger members of The Institution by his advice and help. I myself owe him much. The keen support he gave to Marconi when first the latter came to England was one of the elements that made for Marconi's rapid success. One of the most lovable and popular men ever in our profession, he had, in speaking at meetings, a slow or rather pompous utterance which was most effective.

In 1886 Prof. David Hughes was President. He was born in London, but was educated in America and had a strong American nasal intonation when speaking. He invented the synchronized printing telegraph which, though never, I believe, adopted by the British Post Office, was widely used in America and on the Continent of Europe. He was in consequence a wealthy man, but lived in a most modest fashion. He invented or discovered the microphone and the induction balance, which, prior to the discovery of X-rays, was used to locate metallic objects in the human body. He also discovered wireless transmission of signals, and apparatus made by him for this purpose was recovered after his death by Campbell Swinton and is now in the Science Museum.

John Hopkinson, President in 1890, a Senior Wrangler and Smith's Prizeman at Cambridge, practised as a consulting engineer in London. He invented the three-wire direct-current system of distribution, and was author of many important papers which greatly helped to forward the early practice in electrical engineering.

Sir William Crookes, President in 1891, was educated as a chemist and founded the *Chemical News*. His contribution to electrical science lay in his studies of the production of really high vacua and of electrical discharges through rarefied gases, which led to the discovery of what he called the fourth state of matter, afterwards recognized as streams of electrons. He had a very serious face with his grey pointed beard. but a charming manner.

W. E. Ayrton, President in 1892, was a most remarkable man. At one time with Prof. Perry he was a professor in the University of Tokio, and it was Maxwell who once wrote that the centre of gravity of electricity was in Japan when Ayrton and Perry had begun to tear electricity out of the textbooks and bring it into practical life. In 1880, however, the City Guilds of London started their technical education campaign and in temporary classrooms in Cowper-street, Finsbury, opened technical classes under Prof. Henry Armstrong, Prof. Perry, and Prof. Ayrton, which blazed the trail for entirely new methods of technical training. I was among Ayrton's earliest students, and in 1882 gained the first prize, value £5, and a silver medal in the City and Guilds examinations. Ayrton used to lecture not on a curriculum but on whatever at the time was under study by himself and Perry. Then after the hour's practical work and the hour's lecture the students gathered round and asked questions. One evening a very persistent questioner was W. B. Esson, and at last Ayrton said "Mr. Esson, it is all in Maxwell!" Prof. Perry once remarked at a meeting of The Institution, looking round the room, that two-thirds of those present were or had been Ayrton's students. In fact the first generation of "heavy" electrical engineers were almost entirely Finsbury College men. Prof. Ayrton married twice, his second wife being Miss Marks, who had been a student at the City and Guilds Central Technical College. In 1899 she read a paper before The Institution on "The Hissing of the Electric Arc." This paper had a curious history. Ayrton had conducted a long investigation on the arc and took the notes to Chicago in 1893 to give an account of his results to either the Centennial Exhibition or the St. Louis Electrical Congress, I am not sure which. A negro servant requiring waste paper to light a fire took the notes and burnt them. Ayrton felt he could not do it all again, but his wife took it up and carried it farther than he had done. She was the first woman member of The Institution.

Colonel R. E. Crompton, President in 1895, is indeed a very astonishing personage: at the age of 11 in the trenches before Sebastopol; then organizing mechanical transport for the Indian Army when in his twenties; organizing mechanical transport and portable searchlight units in the Boer War; introducing the electric light into

the Stanton iron-works; builder of the earliest central stations in Vienna and Kensington; reading papers to The Institution on all aspects of central station work; the great protagonist of direct current versus alternating current for electrical distribution, and a constant opponent of the "grid"; but I will say no more as he will in a few minutes speak for himself.

Sir Joseph Wilson Swan was an early member of The Institution, before which he read his famous paper on "Sub-division of the Electric Light." But his appearances at The Institution were rather rare.

Silvanus Thompson, President in 1899, followed Ayrton at the City and Guilds Leonard Street College when Ayrton went to the Central College. He wrote several books on dynamos and motors which were of inestimable advantage to students and designers. He was a very neat man. He used to invite me to his home in Hampstead to discuss dynamo problems, and he had all his references and notes, as I then thought, filed with meticulous care. He was a victim of the Great War. A sincere Quaker, he was terribly torn first by the conflict itself with so many old international friends in the enemy service, and secondly by the division which arose in the pacifist Quaker ranks over the onslaught on Belgium by the Germans.

Gisbert Kapp, President in 1909, of Austrian birth, came to England in 1875 and was shortly afterwards naturalized. In the early eighties when he was working on the problem of predetermining the design and performance of dynamos, I used to go to his house at Wimbledon to discuss these matters and saw much of him. He was a delightful personality and his writings greatly helped the early designers. During the nineties he was in Berlin and edited the *Elektrotechnische Zeitschrift*. He became Professor of Electrical Engineering at Birmingham University in 1904. The last time I saw him was when, on a visit to Birmingham in 1921, he entertained me at his house. He was then working on his oscillating phase-adjuster and we sat up until 2 o'clock in the morning discussing it, just as we did in earlier years. He was ill then and died shortly afterwards.

To speak of those early days and not to mention Ferranti would be impossible, but Ferranti was not a frequent visitor to The Institution, nor did he take much part in its work until in 1910 he became President. In the nineties he had been so engrossed with the creation of the great Deptford station and his manufacturing responsibilities—and, moreover, I think he considered The Institution was not taking the leadership it should do—that he rather stood on one side. His Presidential Address urging the use of electricity for all and everything was a great inspiration, and to read his early struggles and triumphs in his "Life" written by his wife is to absorb an almost unbelievable industrial romance.

And now time prevents me from mentioning others of those early pioneers whom I had the good fortune to know. There were many of whom I should have liked to speak, and their omission is due only to the limitation put upon me by time and your patience. I hope, however, that this sketch of the beginnings of our Institution and of the men who founded our science may have been of interest to you.

The Institution has had prepared a certain number of talking films of the early pioneers. We have only time for part of one such, and I have chosen the grand old man of British electrical engineering, Colonel Crompton, who a few days ago celebrated his 94th birthday.

DISCUSSION ON "THE LIGHTING LOAD—ITS CHARACTERISTICS AND DEVELOPMENT"*

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 7TH NOVEMBER, 1938

Prof. W. Cramp: Dealing first with the effect which the price of lamps exerts on the development of the lighting load, a few years ago I ascertained the retail prices of metal-filament lamps in various countries of Europe. At that time the retail price of a 40-watt "ring" lamp in this country was about 2s. I could only find two countries besides our own in which the price of this lamp exceeded 1s. In France I found myself able to buy retail at 10d. lamps made in England of exactly the same type and, as far as I could tell, of exactly the same quality as were sold in this country at 1s. 8d. I think there is a great deal to be said in favour of the reduction of the price of lamps, for there are instances of working-class houses which have been converted from gas to electric lighting by the landlord, and the tenant has later gone back to gas because mantles cost so much less than electric lamps. That is not the way to increase the lighting load.

Nor does England always get early access to the latest improvements; for I have it on good authority that the coiled-coil lamp was in use in Russia 12 months before it was released in this country.

In connection with the life of lamps, however, there is another important matter. The makers of lamps do not often supply or make the globes in which the lamps are fitted, and it is quite common to find a lamp of, say, 150 watts, put in a globe which is too small for it, so that the temperature rises to such an extent as to shorten the life of the lamp. A firm making both fittings and lamps will usually advise, in a 12-in. sphere, a lamp not exceeding 150 watts in power; yet there are many instances in this neighbourhood and elsewhere of 12-in. globes in which 200-watt or even 300-watt lamps are installed. If the top of the globe is enclosed to keep out flies and dust, it is impossible for a 300-watt lamp to have a reasonable life in a globe of 12-in. diameter, and the life of a 200-watt lamp will be shortened. It is time that steps were taken to keep the householder informed of the relationship between the wattage of the lamps and the surface area of the globe. This is important not only from the point of view of the life of the lamp, but also in preventing the brightness of the glassware being too high for comfort.

I am glad to say architects are beginning to know something about the arrangements which should be made for effective electric lighting. Many now give consideration to this matter when the detail drawings are made. But there is still a long way to go before lighting ceases to be treated as an afterthought. It would not be unfair to say that in Germany, even before the Great War, many architects had more knowledge of electric lighting than is common in England to-day. The reason is that it was necessary there for an architect to have a considerable knowledge of electric lighting in order to pass the examination for his diploma; and I think that this should also be the case in England.

Dr. C. C. Garrard: I find that 24 foot-candles is a very convenient standard for reading, but there are very few offices and very few living-rooms which have anything like this level of illumination.

The author referred to an illumination of 50 foot-candles, which is rather high, as requiring a loading of 15 watts per sq. ft. This means that in a room of, say, 18 ft. × 15 ft., 4 050 watts would be required. I find that such a room can be lighted at 24 foot-candles with 680 watts, costing about 1d. per hour.

Mr. H. Hooper: I should like to know what is the average capital cost per hour of running of the discharge type of lamp compared with the filament type.

A reason why lighting has not been developed as much as the author would like (although I think that the development has been satisfactory) is that the price of lamps is too high. This point affects the bulk user and also particularly the use of electricity for lighting on new large housing estates in suburban areas which are now being erected, particularly in a city like Birmingham.

Perhaps the author would inform us whether he has come across any instances of the following development, which I believe has been tried in Canada. In certain selected areas of newly-developed estates the consumer is provided with an electricity supply for an agreed annual charge, the only restriction being on the maximum demand. In such cases users have a great incentive to increase the lighting and domestic amenities of their homes and thereby add to the comfort of life.

Mr. H. Joseph: The author pleads for a better organization to persuade people to use more electricity for lighting—to use larger lamps and presumably to keep them in use longer. He falls into the common error of assuming that such an organization as he desires must of necessity be formed by the supply authority. It could, however, be brought into being by making use of the services—most willingly available—of all branches of the industry, and in particular the contracting and manufacturing sides, in collaboration with the British Electrical Development Association and the supply section itself. In the early days of the B.E.D.A., circles and area committees existed which were composed of enthusiastic members of all branches, but more recently the activities of the Association have been chiefly confined to the supply side of the industry. These circles still exist, however, in some districts, and are doing excellent work.

* Paper by Mr. W. J. Jones (see vol. 83, p. 289).

Apart from this, a good deal of work is being done by individual contractors and manufacturers, often in co-operation, with a view to the development of better lighting. I plead for a return to the earlier plan to which I have referred.

Mr. E. A. Reynolds: I think the author gives rather exaggerated figures for the likely lighting consumption. I cannot see how it is possible at the present time to give any figures for the proportions of energy used for lighting and other domestic purposes. A very large proportion of the consumers, more particularly the larger ones and those in densely populated areas, are on a domestic tariff in which there is no possible means of distinguishing between lighting and power. How the author calculated the proportions of 77 % and 23 % for lighting and cooking (Table 3) is not obvious.

Turning to Table 4, it appears to me almost incredible that lighting only should account for the increase in annual consumption from 279 units to 706 units in 14 years. I cannot imagine how it is that a householder who used 279 units to give him ordinary illumination in 1922 wants 706 units now. This figure of 706 units means an average of 31 60-watt lamp-hours per day during the year. Taking the proportion between winter and summer lighting hours as 3 : 1, this house is using an average of 45 60-watt lamp-hours per day for 6 winter months, i.e. there are almost 8 lamps in continuous use for 6 hours per day. I do not see how this can be the case in these small houses. Some of the increase shown must be due to other uses of electricity.

One explanation that is not sufficiently stressed by the author is the use of wireless sets. Wireless is responsible for people sitting up later than they used to do, and it is quite usual to wait for Big Ben to strike midnight before going to bed. It has been estimated that wireless is entirely responsible for 15 % of the total domestic lighting consumption.

My first reaction to the elaborate scheme of lighting development adopted in America is that it provides a lot of work for a great many people, but that the increase in revenue would hardly be worth the wages paid.

Mr. H. G. Batson: Domestic lighting should be considered in relation to the average consumer, who occupies a house which a few years ago was known as "the subsidy type." He has an income of about 80s. per week, of which probably some 30s. goes in rent, rates, and insurance, about 6s. in transport, and probably 5s. in midday meals for the wage earner. That leaves a possible maximum limit for electricity of, say, 5s. per week. At the present time the electricity tariff in the area is such that there is a fixed charge of 1s. 2d. per week, and the unit rate is 1d. until a weekly bill of 7s. is reached. Of the average weekly consumption of 33 units, about 30 units are required for water heating, cooking, and room heating, and 3 units for lighting; but the 30 units for general purposes are worth, in terms of the other alternative available services, including the hire of the cooker, only about 2s. 6d. The 3 units for lighting have to be charged at 8d. each in order to cover the remainder of the weekly charge. In this particular case if the lounge and kitchen lighting levels were doubled, that cost would only be reduced to 5½d. per unit. Also, in view of the equivalent value of the general-purpose units in connection with alternative services, any increased use for general purposes merely adds to the cost to be allowed for the lighting.

I have been connected with quite a number of areas where a drop in voltage of over 6 % is common when the heavier pieces of apparatus are put on load; and in the case that I have already cited the electric lamp manufacturers, owing to the continued failure of coiled-coil lamps, advised that 240-volt rated lamps be used on a 230-volt circuit. Now a 10 % drop in voltage means a 33 % drop in light output, so that for the case in question the cost of light is nearer 1s. per unit on what should be a normal supply basis.

I believe I was one of the privileged 50 000 persons mentioned by the author in connection with the light test. I took several checks with the instrument, and for reading by glance I required an intensity of 60 to 65 foot-candles; but when I read for 2–3 minutes and tried again, reducing the level successively to a convenient one, I found that I only required 16 foot-candles. These two levels were checked by an independent light meter of well-known make and found to be considerably in excess of what they were supposed to be. I suggest that the actual level for sustained reading is between the true value of the extremes noted above, probably about 15 foot-candles, or 3 times the usual home intensity.

I suggest that many lighting installations which are at present unsatisfactory could be made perfectly satisfactory by a general spring-clean and the substitution of modern lighting reflectors for the old-fashioned shades.

Mr. J. A. Cooper: Considerably more wattage is required to obtain the same degree of illumination with indirect as with direct lighting. My own experience in using indirect lighting has made me dislike it because of heavy lamp casualties. (I am concerned with a d.c. supply, so that gaseous discharge lamps are not suitable.) It is not possible for me to use lamps hanging inverted—they are fixed at an angle not recommended by the manufacturers. This, coupled with the high temperature reached by lamps in a confined space and close together, leads to a very short lamp life. Could the author give us any information regarding lamps, particularly those available for d.c. circuits, which are likely to have a satisfactory life however they may be fixed?

Mr. F. C. Fuke: Table 4 alone shows that the average consumption for domestic lighting has increased about 2½ times in 14 years. The increases recorded are not wholly accounted for by additional points, but as the author points out are partly due to the use of heavier current-consuming lamps and other appliances. This means that the accessories used with these lamps and appliances are required to deal with heavier loads and are also called upon to handle these heavier loads after many years of service and neglect and when they are no longer young. I am afraid their very reliability is the reason why installed accessories have been ignored during this period of loading-up of circuits. I should like to suggest, therefore, that supply-authority staffs should be instructed to look for well-worn accessories when installing or servicing appliances and, when advisable, to persuade consumers to replace these by others of more modern design and rating. The cost of an accessory is

negligible compared with that of the apparatus for which it is used, and this fact, together with the neat and pleasing appearance of modern accessories, should make the task of persuasion easy. I think accessory manufacturers are well aware of the increased duty which their products are called upon to perform to-day, as is proved by the introduction of the short-slow-break a.c. switch, which is available, I believe, in sizes extending from the tumbler switch to cooker control units.

With particular reference to shop-window lighting, I think the days of specifying a 10-ampere switch for a 5-ampere load are over; the modern switch will carry and break its rated capacity with certainty.

Finally, I should like to mention that as the manufacturers are not in contact with consumers they must rely upon the supply authorities and contractors to see that installed accessories are replaced when they reach the end of their useful life.

Mr. F. L. Cator: With regard to the author's last demonstration, showing the effect of ultra-violet light upon materials treated with fluorescent powders and dyes, it has occurred to me that he may be able to suggest some methods whereby this phenomenon could be made use of in A.R.P. black-outs. For instance, could fluorescent paint be applied to the most important traffic signs in a city, and these signs be illuminated by a "black" lamp during an air raid? Again, is it not possible that fluorescent paint and ultra-violet light might play a useful part in making visible the most important switches and meters in a power station during a black-out?

Mr. R. H. Rawll: The author implies that supply authorities should reduce the price of energy for lighting purposes, but I think it is only fair to say that one of the difficulties which most supply authorities experience in dealing with this matter is that the average undertaking to-day still depends upon its lighting load for the major portion of its revenue. It is true that there are differences in the circumstances of supply undertakings, such as those with a very large industrial load or, on the other hand, those possessing a large domestic load; but I think it is safe to say that in most cases the majority of actual revenue comes from the lighting load.

Difficulty is often experienced when an attempt is made to pare down a lighting tariff, because, whereas with tariffs for other loads a reduction of a fraction of a penny per unit does not usually have any great effect on the revenue, yet it makes all the difference to the annual balance sheet if the tariff for lighting is varied. The only solution is to introduce a tariff which will cover the supply of current for all purposes to a particular consumer. Considering, for example, commercial premises in a large city, if one were going to introduce a general two-part tariff for such premises, one would first of all have to obtain the maximum demand of every commercial consumer in the city. (This would naturally occupy some considerable time, as the necessary observations would have to be taken over a period of at least 12 months.) One would then have to work out a tariff which would give a total revenue somewhere within the region of the total revenue obtainable at the present time with the existing tariff. This, it will be conceded, is no small problem. Supply authorities are often unjustly criticized for not putting forward attractive tariffs for business premises, when in numerous cases it is a very difficult matter for them to do so.

I am very interested in the author's remarks regarding lighting development officers in the United States. It would be interesting to know whether other classes of domestic load (e.g. cookers and water heaters) in that country are developed by sales staffs who are not employed by the supply authorities.

[The author's reply to this discussion will be published later.]

SCOTTISH CENTRE, AT EDINBURGH, 13TH DECEMBER, 1938

Mr. William Ross (Glasgow): The author instances the case of a development officer who secured 100 kW of commercial lighting per annum, producing a revenue of about £700 with a charge of 2d. per unit and a 10 % load factor. Perhaps I might suggest a cheaper way of getting an increase in the lighting load. Outside the range of the shops there are in most towns rows and rows of dark streets in which no outside lighting is installed by any of the owners or tenants. If it could be brought home to these people that they can get outside lighting for the whole of an evening for something under 1d. they might be encouraged to install more of such illumination and thus improve the load factor of lighting.

Mr. E. Seddon (Edinburgh): I agree with the author that we should encourage consumers to employ higher lighting levels than those which obtain at present, but I submit that we should also encourage lighting of a more uniform character.

There can be no doubt that the ideal method of lighting is one where the source of light is obscured from view; and in this connection I should like to ask the author whether any industrial establishment has tried out a system of lighting using high-power floodlamps with their beams directed on to metal reflectors surfaced with white vitreous enamel which can be washed at frequent intervals.

Another method which appeals to me as being equally applicable to large stores and to factories would be to place each source of light below a continuous metal reflector running the whole length of the building, with the lower portion of the globes partially obscured in order to avoid spots of light. Such an arrangement would make for more even illumination than can be obtained with independent light sources.

In general, I think it may be said that the larger the individual lamp, the lower is the total cost per lumen output, and therefore lamps of large wattage should be encouraged providing the light sources can be suitably diffused.

In connection with the raising of lighting levels, we should realize that in summer we are subject to daylight intensities of the order of 10 000 foot-candles, and in winter we can get values indoors close to windows of 100 foot-candles; yet the majority of our industrial

establishments could not show an average intensity during hours of artificial lighting of more than 1–2 foot-candles on their work tables.

We are doing what we can in Edinburgh in the direction indicated by the author. Ten years ago our sales of lighting units amounted to 24 % of the total, and although since then the total sold for all purposes has been doubled, the proportion of lighting units has only fallen to 22·75 %; and if the lighting included with power units were taken into account I do not think there would be any difference in the percentage as compared with 10 years ago. These lighting units account for 47 % of the total revenue from the sale of energy.

Speaking of the progress of lighting methods in this country as compared with America and the Continent, I do not think that the general quality of shop lighting in this country differs much from that prevailing abroad, although on a recent visit to Budapest I saw some of the finest examples of shop-window lighting that I have ever seen. Regarding the position of street lighting, we are well ahead of most countries in this direction.

I should like to ask the author what has been done with regard to correcting the colours of lamps so as to reduce eyestrain to the minimum. I understand that certain investigations have shown that a preponderance in the red and yellow bands is harmful to the retina of the eye. I recently tried a 250-watt mercury lamp in my office, with fairly satisfactory results—the lamp burned for 2 600 hours. I found it an advantage to have a metal lamp on each side of the mercury lamp in order to introduce some red rays. The use of mercury-vapour lamps in workshops where there is moving machinery is not very satisfactory, on account of the stroboscopic effect associated with gas discharge lamps. I tried some of the earlier supplies of internally sprayed discharge lamps, but found that the powder came away and fell to the bottom of the lamp after a very short life. I should like to ask the author whether this disintegration occurs with the more recent supplies of these lamps.

Can metal-filament lamps be purchased with strengthened filaments for burning upsidedown in candlestick fittings? I have had many complaints of short life of the standard lamps, and in my own home I find I cannot get more than an average of 300 hours from lamps burning in this way.

Mr. J. Eccles: The units consumed in lighting can be considerably increased and the load factor improved by the adoption of a two-part tariff. In Edinburgh the fixed component of this tariff is based on the kilowatts of installed lighting, and we have met the author's criticism of this basis, at least to some extent, by grading the rate per kilowatt as shown in Table A.

Table A

Installed kilowatts	Rate per kilowatt
First 2	£7
Next 3	£6 15s.
Next 15	£6 10s.
Next 30	£6
All over 50	£5 10s.

The running charge is $\frac{3}{4}$d. per unit in every case. Table B shows typical results obtained from the adoption of this tariff. It will be noted that in all cases the consumption has increased, and in every case save one the annual load-factor expressed as $\frac{\text{Units consumed}}{\text{Installed kW} \times 8\,760}$ has also increased.

The major part of this paper is concerned with methods for increasing the sale of lighting units, but no doubt the author would agree that the quality of the lighting is of equal importance to the quantity of light. In this respect quality must be gauged by uniformity as much as by intensity. After considerable experience in industrial establishments where attention to fine detail is an important part of the process, one is driven to the conclusion that absolutely uniform shadowless lighting, where the sources of light are not exposed to view, produces a minimum of ocular fatigue. The intensity need not be very high as long as the illumination is uniform everywhere within the view of the operatives. The reason for the absence of fatigue under such conditions is not far to seek when one remembers that with each change in intensity, the pupil has to perform a muscular adjustment, which, if repeated often, inevitably produces strain.

Table B

Type of premises	Data for year prior to adoption of 2-part tariff			Similar data for year 1937–38	
	Year	Consumption	Load factor	Consumption	Load factor
		units	%	units	%
Departmental store	1929–30	100 288	22·9	149 450	31·2
Hotel	1929–30	29 608	20·0	58 582	22·1
Furniture shop	1929–30	41 319	11·0	72 289	18·9
Draper's shop	1933–34	137 564	21·0	150 914	23·1
Jeweller's shop	1933–34	3 773	6·2	8 154	13·3
Grocer's shop	1933–34	2 974	9·1	4 160	12·7
Butcher's shop	1933–34	1 453	18·5	1 999	17·5
Bookseller's shop	1934–35	1 470	16·0	2 026	22
Ice-cream saloon	1935–36	2 570	11·1	3 871	16·7

I should like to have some more information with regard to Fig. 3. Is the load factor of the 50 shops the average load factor, and, if so, is it the weighted average? Furthermore, has diversity of maximum demand been taken into account, and, if not, will the author say what is the effect of diversity, i.e. what is the load factor of the whole lighting supply to these 50 premises for each year under review?

Mr. H. C. Babb: I think that the author's suggestions, while applicable to cities and towns, are very optimistic in relation to rural areas.

In connection with shop lighting, we have tried putting in free installations and properly lighting shop windows, on the understanding that if after a given period the shopkeeper is satisfied he pays for the installation, if not we undertake to take it out again. In every case we have had to take the equipment out again, and the reason given has been that in towns of this nature, which are situated adjacent to a city, it matters not what class of lighting the shopkeeper installs his sales will not increase a halfpennyworth; and I think there is a good deal to be said for the argument. Lighting development to a large extent depends on the cost of energy, and until the Central Electricity Board revise their tariffs I do not see how distributors, who have to purchase at the Board's tariffs, can very well alter their lighting charges.

So far as schools in Scotland are concerned, I do not agree that their lighting load misses the time of maximum load on the undertaking. The East Lothian schools have electric heating, and children cannot be sent into a school at 9 a.m. unless the school is warm: the result is that our maximum loads usually occur in the early morning.

I should like to know what basis the author favours for the two-part tariff. What basis does he favour for the standing charge for shops: rateable value, installed load, or measurement?

According to Table 10 the street-lighting hours for "half night" are 1 800 per annum and for "all night" are 4 000. So far as our street lighting is concerned, "half night" lamps burn till 11.30 p.m. and then go on again at 5 a.m. and burn till daylight. In Scotland the hours per annum are only 1 400 for "half night" and 3 720 for "all night." I assume, therefore, that the average figures for Great Britain are quoted by the author.

Mr. G. F. Moore: My experience of lighting development is that the public are indifferent to the advantages of good lighting because they are unable through ignorance to appraise its value.

It would be of interest to me to know how many factory owners have taken advantage of the recent offer of expert advice on the lighting of their premises for conformity with the new Factories Act.

In a discussion of this nature I am bound to draw attention to the apparent short life of lamps of the "striplite" type. My experience is that as at present manufactured such lamps are very unreliable, and I would suggest that their wide field of application justifies a fair amount of research into the question of their improvement, both in regard to life and in regard to light output.

Mr. W. J. Cooper: I should like to ask the author where his figures of units used for lighting were obtained, because in most undertakings a large percentage of the units sold are sold on the basis of a two-part tariff and it is impossible to separate the lighting units from the units used for other purposes. If the author's figures have been taken from the Commissioners' Returns I do not think their use can be justified in connection with lighting.

[The author's reply to this discussion will be published later.]

DISCUSSION ON "FIRE PRECAUTIONS IN MAJOR ELECTRICAL STATIONS"*

WESTERN CENTRE, AT BRISTOL, 13TH FEBRUARY, 1939

Mr. T. B. Rolls: Reference is made in the paper to a non-inflammable alternative to oil, namely Pyranol, and it is suggested that its use is confined to small transformers. Is it applicable to some of the smallest transformers, i.e. potential and current transformers? Also, can it be used as an alternative to oil or compound for busbar chambers?

Care appears to be necessary when installing fire-fighting equipment which is dependent on water pressure. Mains water pressure may be sufficient to deal with fire-fighting requirements in peace time; but under A.R.P. conditions the mains may have to deal with fire scattered over the area which they serve and there may not be sufficient pressure for the correct working of spray or foam apparatus.

With regard to fire sectioning, a second busbar added to Fig. 1(*d*) would provide true sectioning if it did not pass through the chamber occupied by the section switch. The two halves might be connected together by cable or, alternatively, not linked, the latter being less costly and also less flexible for testing, etc.

Mr. A. C. Warman: What experience has the author had in regard to the protection of alternators themselves against internal fire, and what measures would he suggest for (*a*) the limitation or restriction of the air circulation which is likely otherwise to fan the fire and support combustion; (*b*) the introduction of CO_2 gas into this closed circuit in order to quench the flames.

Is it good practice to keep the CO_2 gas cylinders and the valve control gear for these, outside the building they are designed to protect? I suggest that it is *not*, in view of the necessary extensions to the comparatively frail operating wires, small pulleys, etc., which could so easily be put out of action by an explosion.

I am doubtful whether any real advantage is to be derived from the use of Buchholz relays on power transformers, my own experience being that for months after the first putting into commission of the transformers, the relays are constantly tripping due to air being expelled from the windings, oil, etc.

Mr. W. Hill: Any fire-fighting system which it is proposed to adopt has to be considered largely from the point of view of A.R.P. Bearing this in mind, would the author recommend large fixed fire-fighting installations? I have in mind that if the power station or large sub-stations are damaged by high-explosive bombs which may burst the transformers and start a fire, the fire-fighting apparatus may be put out of action by the bursting of some of the pipes. I suggest it would be better to install more semi-portable apparatus.

I should be glad of more information as to the fire-fighting media which are available, and particularly in regard to methyl bromide, which the author mentions on page 295 (vol. 81).

A previous speaker suggested that 400-volt switchgear need not be sectionalized. On the other hand, the author refers to fires started by low-voltage gear and later to electrical cooking apparatus used by members of the staff. The small experience I have had of fires and the breakdown of insulation leads me to suggest that 400-volt gear should be sectionalized, if only to be able to ensure continuity of supply, because I agree with the author that it is on low-voltage gear that fires frequently occur.

Mr. G. H. Bowden: Efforts based on one experience of fire are often illogical and sometimes unduly expensive. I find nothing to criticize in the paper, but I should like to add to the remarks on arrangement of gear, for I feel that is all-important. Attention is drawn to the degree of risk involved, but since the paper was written we have been asked to provide for contingencies not previously considered. I consider the root of all our difficulties to be the perpetuation of the main-busbar idea, which does not satisfy modern conditions and the requirements of the high-power station.

We cannot hope in the face of load development to match up gear of 1939, with extensions in 1949, without repeating the complication of the gear which involves disproportionate expenditure; that is a feature of so many present stations, especially where a multiplicity of busbar voltages are in use.

The busbar-section switch of heavy current rating is a problem both in design and in expense. To-day no important load depends entirely on a single feeder, and no system on the operation of a single generator, and I therefore fail to realize the necessity for double busbars. The complication of selector gear that goes with them does not make for reliability; simplicity is essential.

The author advocates the development of the unit principle; that system has much to commend it, for it avoids any point that is vital to the operation of the whole system. I am thinking of the arrangement in which each generator switch has a busbar to itself together with a number of feeders, all contained within a separate chamber or building. Tie busbars are of course required, but are not vital, for interconnection between distributing centres often serves the same purpose as busbar reactors in the more conventional layout. The physical separation of gear enables fires, when they do occur, to be more easily dealt with, and the smaller number of connections to one busbar permits the more satisfactory application of busbar protective systems. In the event of false operation of relays the effect is not so serious. Lastly an

* Paper by Mr. F. C. WINFIELD (see vol. 81, p. 289).

important feature is the ability to treat extensions without the limitations of continuing one type of gear, to employ improvements in design, and to purchase on the open market.

Mr. R. W. Biles: The author makes a valuable contribution towards the most efficient means of combating the fire risk. It is natural for those concerned when considering the matter to endeavour to provide the most economical arrangement under the circumstances, and it occurred to me that the author might have in his mind the minimum which could be done in particular cases. For instance, one would anticipate that below certain voltages and rupturing capacities of switchgear the risk would be somewhat less, and efficient fire-fighting equipment would be all that was necessary. Again, apparatus which avoids the use of oil or other inflammable liquids would not require sectionalizing and protection.

There is no doubt that the amount of protection to be provided must be guided by the importance of the service to be protected. Most of our difficulties arise when protecting plant which is already in service and which requires reconstruction, for there should be no serious difficulties in the way of the laying-out of new plant such that the fire risk is at a minimum.

Since the paper was first read we have had to give careful consideration to the protection of buildings, etc., under the A.R.P. scheme. Whilst the A.R.P. modifications are mainly devised for protection from effects external to substations and apparatus, at any rate a common requirement of both schemes is adequate fire-fighting equipment.

Mr. F. C. Winfield (*in reply*): In reply to Mr. Rolls, I am not aware that Pyranol has actually been used for current- and potential-transformer work; and, whilst it could without question be used, it seems to me that—at any rate for the higher-voltage potential-transformer work—its use would not be desirable, as special insulating materials have to be employed for it which would probably not be conducive to the high degree of reliability required in potential-transformer windings. The use of Pyranol as an alternative to oil or compound for busbar chambers is again possible but difficult owing to the special insulation requirements. It is also likely to be expensive. I agree with Mr. Rolls that the question of water supply pressure in A.R.P. fire-fighting conditions is a difficult one. The situation is at present being actively canvassed by the various A.R.P. investigators and the water supply companies.

I agree with Mr. Rolls's remarks about Fig. 1(*d*), and have employed the arrangement he suggests in many jobs of moderate importance. For more important work, however, I prefer to employ arrangements (*e*) or (*f*).

I assume Mr. Warman is referring to normal steam-driven alternators having closed air circuits. I cannot quote a single case in my direct experience of serious damage by fire in such an alternator and, if such did occur, I should be inclined to blame the protective equipment. The volume of air available to support combustion in a closed air system is relatively small and the winding material relatively non-inflammable, and the two factors seem in themselves to give all the safeguard necessary. I doubt whether there is any real case for the introduction of CO_2 gas.

It seems desirable to keep CO_2 gas cylinders outside the chambers they are designed to protect, though not necessarily outside the building as a whole. I like in large installations to provide two alternative points of control, one right at the cylinders themselves and the other at some point which is more convenient for operation.

Regarding Buchholz relays, I agree that for some time after the installation of a transformer air will be given off by the windings, and the relays should not be connected to trip during this period. If this period is unduly prolonged, however, I should, in a forced-cooled installation, examine my oil pumping arrangement as it would probably be found that air was gaining access from the outside through the pump glands. For this reason I prefer the completely submerged oil pump for this work.

In reply to Mr. Hill, it seems to me that peace-time conditions are usual and A.R.P. conditions are exceptional. I prefer, therefore, to design an installation for its peace-time uses and then to consider what additional precautions are necessary for A.R.P. conditions. In all cases I look upon fixed fire-fighting installations as a provision whose object is to limit fires but which must not be assumed to be absolutely foolproof and should be backed by general portable equipment and by the services of the public authorities. I entirely agree that for A.R.P. work the number of portable equipments should be materially increased.

I find much to sympathize with in Mr. Bowden's remarks. In practice the reason for main busbars lies in the capacity they confer to collate feeder loads and distribute the total equally or in any special combination over all the generators in a given station, and vice versa, which is an important factor in the economy and flexibility of generation and transmission. The alternative, often called "synchronizing at the load," proves in practice less flexible and more costly, and it is significant that the particular school of thought which proclaimed this in the U.S.A. has been very quiet for some years. None the less, I feel that sound engineering will best be achieved by some compromise between the two points of view.

If we accept a system of main busbars, the duplicate busbar is simply a tool to permit free maintenance and extension. Since busbars themselves must be maintained, the condition of having to interrupt a large number of feeders simultaneously for this purpose would occur too frequently to be practical if only a single busbar were used in a multiple feeder and plant arrangement. The whole subject is, however, much too large to be dealt with adequately here.

Regarding Mr. Biles's remarks, I am in entire agreement with the point of view which he expresses, but I feel that it is not possible within the scope of a brief reply to attempt to indicate any definite lines of demarcation in the application of fire-fighting equipment and arrangements. As he says, in new equipment the problem is fairly straightforward, but in existing equipment the local conditions applying to each job must govern the solution adopted to such a large degree that it is not practicable to lay down general rules.

PROCEEDINGS OF THE INSTITUTION

941ST ORDINARY MEETING, 19TH JANUARY, 1939

Mr. Johnstone Wright, Vice-President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 5th January, 1939, were taken as read and were confirmed and signed.

Messrs. A. L. Lean and W. S. Sholl were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, it was reported that the members whose names appeared on the lists (see vol. 84, page 298) had been duly elected and transferred.

A paper by Mr. N. F. T. Saunders, B.Sc., Associate Member, entitled "The Design of Fractional Horse-Power Induction Motors" (see page 161), was read and discussed.

A vote of thanks to the author, moved by the Chairman, was carried with acclamation.

942ND ORDINARY MEETING, 2ND FEBRUARY, 1939

Dr. A. P. M. Fleming, C.B.E., M.Sc., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 19th January, 1939, were taken as read and were confirmed and signed.

The President announced that the Council had elected Sir Archibald Page (Past President) an Honorary Member of The Institution, and that the seventeenth award of the Faraday Medal had been made to Dr. W. D. Coolidge.

A list of candidates for election and transfer, approved by the Council for ballot, was taken as read and was ordered to be suspended in the Hall.

A paper by Messrs. L. W. Hayes, Member, and B. N. MacLarty, O.B.E., Associate Member, entitled "The Empire Service Broadcasting Station at Daventry" (see page 321), was read and discussed.

A vote of thanks to the authors, moved by the President, was carried with acclamation.

943RD ORDINARY MEETING, 23RD FEBRUARY, 1939

Dr. A. P. M. Fleming, C.B.E., M.Sc., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 2nd February, 1939, were taken as read and were confirmed and signed.

The President announced that, during the month of January, 3 954 donations and subscriptions to the Benevolent Fund had been received, amounting to £1 927. A vote of thanks was accorded to the donors.

A list of candidates for election and transfer, approved by the Council for ballot, was taken as read and was ordered to be suspended in the Hall.

Messrs. L. J. N. Kirkby and A. E. Quenzer were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, it was reported that the members whose names appeared on the lists (see vol. 84, page 418), had been duly elected and transferred.

A paper by Messrs. G. H. Fletcher, Member, and A. Tustin, M.Sc., Associate Member, entitled "The Metadyne, and its Application to Electric Traction" (see page 370), was read and discussed. A demonstration of the metadyne was given in connection with the paper.

A vote of thanks to the authors, moved by the President, was carried with acclamation.

944TH ORDINARY MEETING, 9TH MARCH, 1939

Dr. A. P. M. Fleming, C.B.E., M.Sc., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 23rd February, 1939, were taken as read and were confirmed and signed.

The President announced, that during the month of February, 773 donations and subscriptions to the Benevolent Fund had been received, amounting to £355. A vote of thanks was accorded to the donors.

Messrs. H. L. Weller and C. Verity were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, it was reported that the members whose names appeared on the lists (see vol. 84, page 515), had been duly elected and transferred.

A paper by Mr. F. W. Lawton, Member, entitled "The Design and Operation of Hams Hall Power Station" (see page 469), was read and discussed.

A vote of thanks to the author, moved by the President, was carried with acclamation.

ACTIVITIES OF THE INSTITUTION

A circular setting out the general policy of The Institution during the present war conditions is enclosed with this issue of the *Journal* to every member.

MEMBERS ON SERVICE WITH H.M. FORCES

The Secretary would be glad to receive, for publication in the *Journal*, the names of members of The Institution who are serving with H.M. Forces, together with particulars of their rank and the unit in which they are serving. It is also proposed to publish lists of promotions, transfers, military honours awarded, etc. All such particulars, both in regard to a member himself and in connection with other members of which he may have knowledge, should be sent to the Secretary as early as possible so that the Institution records can be kept up to date.

VOLUNTARY NATIONAL SERVICE CENTRAL REGISTER

At the request of the Central Register Advisory Council of the Ministry of Labour The Institution circularized its members (except Companions and Students) last April, asking that those who were in a position to take up work of national importance in an emergency should complete and return duplicate registration cards giving details of their experience, one copy of which would be passed to the Ministry, whilst those members who were unable to volunteer were asked to return one red card for the Institution's records only.

Up to the 1st October the response to this appeal has been as follows:—

As volunteers	5 251
For record purposes	2 819
	8 070

It is earnestly hoped that, in order to complete the Institution's records, those members who have not done so will return the red registration cards.

The Register was put into operation by the Ministry on the outbreak of war and a number of calls have already been made on certain sections, while for other sections no demand necessitating active consideration of the names on the Register has arisen and may not arise for some time.

Close co-operation is being maintained with the Ministry through the Electrical Engineering Sub-Committee of the Advisory Council of the Central Register.

OVERSEAS ACTIVITIES

Argentina

At meetings of the Local Centre held on the 28th July and 4th August, 1938, a number of short papers were read on the subject of "The Anticipation of Demand and Advance Planning for Public Services." Mr. C. G. Barker, Chairman of the Centre, dealt with telephone services; Mr. F. J. Brieux with electric supply services; Mr. K. N. Eckhard, Member, with suburban electric traction; Mr. G. Clarke with railway passenger traffic; Mr. L. Perkins with transport; Mr. W. C. Martin with water supply; Mr. G. W. Munday, Associate Member, with railway power and lighting services; Mr. J. L. Smith with gas supply; and Mr. R. W. Poots, B.Sc.(Eng.), Graduate, with telephones.

At a meeting held on the 24th August, 1938, Mr. C. G. Cousins, B.Sc.(Eng.), Associate Member, read a paper entitled "Air-Conditioning of Steam Trains, with special reference to the 'Cordobés.'"

At a meeting held on the 23rd September, 1938, Mr. J. K. Clark read a paper entitled "A Review of Electric Traction in Europe." The paper was illustrated by lantern slides.

At a meeting held on the 10th November, 1938, Mr. E. Berry, Associate Member, delivered a lecture entitled "The Modern Trend of Science." The lecture was illustrated by a number of experiments and demonstrations.

The Annual General Meeting of the Centre was held on the 9th December, 1938.

Australia

Queensland.

A Joint Meeting of local members of the I.E.E. and members of the Brisbane Division of The Institution of Engineers, Australia, was held on the 19th August, 1938, at Brisbane. The subject for discussion was "Industrial Administration," and it was introduced by Mr. A. S. Deacon, Associate Member I.E.E., and by Mr. R. J. Donaldson of the Australian Institution.

The annual social gathering of the local I.E.E. members was held on the 30th September, 1938, at the Belle Vue Hotel, Brisbane, when 60 members and guests were present. Mr. J. S. Just, Local Hon. Secretary and Treasurer, welcomed the representatives of kindred scientific Institutions.

The Christmas Luncheon of the local members took place on the 15th December, 1938, at the Hotel Cecil, Brisbane, and was attended by 18 members and an official guest, Mr. S. F. Cochran, Chairman of the State Electricity Commission, who addressed the gathering.

A further meeting of the members was held on the 4th May, 1939, at the Royal Queensland Aero Club, Archerfield. Mr. E. J. Brunckhorst, the Club's chief engineer, delivered an address dealing with the method of tabulating progress reports on the materials used in aeroplane manufacture and the steps taken to ensure that only materials of standard quality are used. The Address was followed by a discussion, at the conclusion of which Mr. Just moved a vote of thanks to the author and to the Club.

At a further meeting held on the 19th May, 1939, Mr.

A. McCulloch, M.E., read a paper on "The Protection of Overhead Transmission Lines against Lightning." The attendance numbered 32 and an interesting discussion took place.

South Australia.

A social function was held at the Hotel Richmond, Adelaide, on the 27th October, 1938, at which 15 local members of the I.E.E. and 8 guests were present. During the evening a paper entitled "Electrical and other Impressions of a Trip through the U.S.A. and Europe" was read by Mr. R. H. M. Lea, B.E., and Mr. L. J. Wigan, B.E., Associate Members, who had been investigating for the Adelaide Electric Supply Co. recent developments in steam boiler and turbine plant. Mr. J. R. Brookman, M.E., Member, also read a short paper on a proposed high-voltage transmission line to connect the undertaking of the State Electricity Commission of Victoria at Yallourn with the Adelaide Electric Supply Co.'s system.

A Joint Meeting of the local members of the I.E.E. and The Institution of Engineers, Australia, was held on the 9th December, 1938, at which Mr. J. M. Donaldson, M.C., Past-President I.E.E., delivered an Address on "The Development of Electric Supply in Great Britain." There was a very good attendance and a full discussion.

Victoria and Tasmania.

A Joint Conversazione of the local members of the I.E.E., The Institution of Civil Engineers, and The Institution of Mechanical Engineers, was held at the "Wattle," Melbourne, on the 8th December, 1938. The function, which was attended by 100 members and their friends, was very successful. During the evening Prof. E. Skeats delivered an illustrated talk on his recent visit to Iraq and Iran.

Ceylon

At a meeting arranged by the Local Committee and held on the 14th October, 1938, Major C. H. Brazel, M.C., in the chair, the paper by Mr. E. T. Norris, Member, entitled "The Moving-Coil Voltage Regulator" (see vol. 83, page 1), was read on behalf of the author by Mr. J. Wilson, B.E., Associate Member. An interesting discussion followed, at the conclusion of which a vote of thanks to the author and to Mr. Wilson for introducing the paper was carried unanimously.

China

At a meeting held on the 3rd October, 1938, and arranged by the Engineering Society of China, in conjunction with the I.E.E. China Centre, The Institution of Civil Engineers (Shanghai Association), and The Institution of Mechanical Engineers (China Branch), Mr. J. Haynes Wilson, M.C., Associate Member I.E.E., delivered his Inaugural Address.

On the 24th October, 1938, before a meeting of the China Centre of the I.E.E., in conjunction with the Engineering Society of China and the associated Institutions, Mr. S. Flemons, Chairman of the Centre, presided, and 34 members and guests were present. A paper by Captain A. B. Whatman, B.A., Associate Member I.E.E., entitled "The Ionosphere," was read by Father P. Lejay on behalf of the author, who had been transferred to Hong Kong. In the discussion which followed the reading of the paper Messrs. W. L. E. Miller, J. Haynes Wilson, M.C., N. W. B. Clarke, and H. Berents took part. A vote of thanks, proposed by the Chairman, to the author and Father Lejay, was carried with acclamation.

At a Joint Meeting of the associated Institutions held under the auspices of The Institution of Civil Engineers (Shanghai Association), on the 14th November, 1938, a paper on "Air-Raid Precautions" was read by Mr. W. P. Rial, B.Sc.

A further Joint Meeting was held under the auspices of the I.E.E. China Centre, on the 28th November, 1938, when a paper, entitled "Electrical Interference with Radio Reception," was read by Mr. W. L. E. Miller, Graduate I.E.E., 32 members and guests were present and the following took part in the discussion: Messrs. N. W. B. Clarke, W. C. Gomersall, H. Berents, J. Haynes Wilson, M.C., C. R. Webb, W. F. Gent, and F. J. Hookman, B.Sc. A hearty vote of thanks to the author, proposed by Mr. Gomersall, was carried with acclamation.

A further Joint Meeting was held under the auspices of The Institution of Mechanical Engineers (China Branch) on the 12th December, 1938, when a paper entitled "The Science of Lubrication" was read by Mr. H. G. B. Perry, B.Sc., M.E.

A Meeting of the Engineering Society of China and associated Institutions was held on the 9th January, 1939, when a paper entitled "Chemical Work and Problems in the Power Industry" was read by Mr. J. K. Rummel, B.Sc.

The Annual General Meeting of the I.E.E. China Centre was also held on the 9th January, 1939, 14 members being present. Mr. W. C. Gomersall, Vice-Chairman, presided. The Report of the Committee for the year ended 30th September, 1938, was presented and adopted.

A further Joint Meeting of the associated Institutions was held under the auspices of the I.E.E. China Centre on the 13th February, 1939, at which Mr. W. C. Gomersall, Associate Member I.E.E., read a paper on "Commercial Engineering in China." Fifty-one members and guests were present and the following took part in the discussion: Messrs. H. Graham, A. J. Percival, W. L. E. Miller, J. Haynes Wilson, M.C., and A. H. George, C.M.G. (Commercial Counsellor, British Embassy). At the conclusion of the discussion Mr. J. Haynes Wilson moved a vote of thanks to the author.

A further Joint Meeting was held under the auspices of The Institution of Mechanical Engineers (China Branch) on the 27th February, 1939, at which Mr. J. R. G. Barter, B.A., read a paper on "Handling Petroleum Products."

At a Meeting of the Engineering Society of China and associated Institutions, held on the 13th March, 1939, a paper by Mr. N. Maas, B.Sc.(Eng.), entitled "The Engineer and his Locus Standi" was read.

A further Joint Meeting was held under the auspices of The Institution of Mechanical Engineers (China Branch) on the 27th March, 1939, when a paper on "The Modernization of Industrial Power Plants" was read by Mr. S. Stucken, B.A., Associate Member I.E.E.

A further Joint Meeting was held under the auspices of The Institution of Mechanical Engineers (China Branch) on the 17th April, 1939, when a paper by Mr. J. A. Bonnyman, M.B.E., entitled "Some Notes on Ships' Propellers, with special reference to the Manufacture of Screw Propellers," was read.

A further Joint Meeting was held under the auspices of The Institution of Mechanical Engineers (China Branch) on the 8th May, 1939, when a paper on "Modern Water-Tube Boilers," by Mr. C. W. Johnson, was read.

The Annual Dinner of the I.E.E. China Centre was held at the Shanghai Club on the 19th May, 1939, when Mr. S. Flemons, Chairman of the Centre, presided over a gathering numbering about 80 members and guests. The latter included Sir Herbert Phillips, K.C.M.G., O.B.E. (H.B.M. Consul-General, Shanghai), Mr. A. H. George, C.M.G. (Commercial Counsellor, British Embassy), Sir Robert Calder-Marshall, K.B.E. (Chairman of the British Chamber of Commerce), and Mr. W. J. Keswick (Vice-Chairman, Shanghai Municipal Council). In proposing the toast of "The Institution," Mr. Flemons gave a brief account of the foundation and early days of The Institution and then mentioned a few items of outstanding importance in his own sphere of electrical engineering with which he had come into contact during his recent visit to Europe and America. In conclusion he referred to the importance of National Service and the technical knowledge and experience of electrical engineers which could be called upon in time of emergency.

India

Bombay.

The annual social gathering of local members was held at the Eros Café, Bombay, on the 17th November, 1938, and proved most enjoyable; 48 members and guests were present.

At a meeting of local members held on the 30th November, 1938, a paper by Mr. B. B. Pradhan, M.Sc.Tech., Associate Member, entitled "The Training of Electrical Engineers" was read by Mr. M. V. Pantvaidya on behalf of the author. The meeting was attended by 63 members and guests and an interesting discussion took place.

At a meeting held on the 12th January, 1939, a paper by Mr. J. T. Guthrie entitled "Electronic Organs" was read and discussed; 49 members and guests were present.

At a meeting held on the 28th February, 1939, at which 46 local members and guests were present, a paper by Mr. H. F. Akehurst, B.Sc., Associate Member, entitled "Recent Progress in the Manufacture of Super-Tension Cables," was read and discussed.

A meeting was also held on the 18th April, 1939, at which Mr. H. J. Mulleneux, Associate Member, read a paper entitled "The Design and Construction of an Electrical Track-recording Car"; 89 members and guests were present.

A visit to the Central Telegraph Office, Bombay, attended by 86 local members, took place on the 15th July, 1929.

Calcutta.

At a meeting on the 24th June, 1938, attended by 21 local members and 3 guests, Mr. W. H. Adcock, B.Sc., Associate Member, read a paper entitled "The Lighting Load—its Characteristics and Development."

The first meeting of the 1938–1939 session took the form of a number of short talks on "Interesting Incidents in the History of Electrical Engineering," the subject being introduced by Mr. F. T. Homan, Member. The meeting was well attended, 42 members and a guest being present.

A further meeting, at which 32 local members and 3 guests were present, was held on the 9th February, 1939, when a paper was read by Mr. F. G. Hyland, Associate, entitled "The Effects of Lightning, and Precautions to be adopted for the Protection of Overhead Lines."

A visit to the new generating station of the Calcutta Electric Supply Corporation, Ltd., at Mulajore, took place on the 2nd March, 1939. The visit proved very popular, 59 members and 18 guests taking part.

A further meeting, attended by 26 members and 2 guests, was held on the 13th April, 1939, when Mr. A. N. Bromley read a paper entitled "Modern Broadcast Receivers."

Lahore.

A meeting arranged by the Lahore Local Committee was held on the 27th April, 1939, at which the paper by Mr. H. S. Hvistendahl, B.Sc.(Eng.), Associate Member, entitled "Thermal Power Plants for Peak-Load and Emergency Service" (see vol. 84, page 305), was read and discussed.

Madras.

A meeting arranged by the Local Committee was held on the 22nd December, 1938, to discuss the question of increasing the activities of The Institution in the Madras area.

A social function took place at the Connemara Hotel on the 28th February, 1939, Mr. H. Burkinshaw, Member, acting as host for the occasion. The attendance was 65.

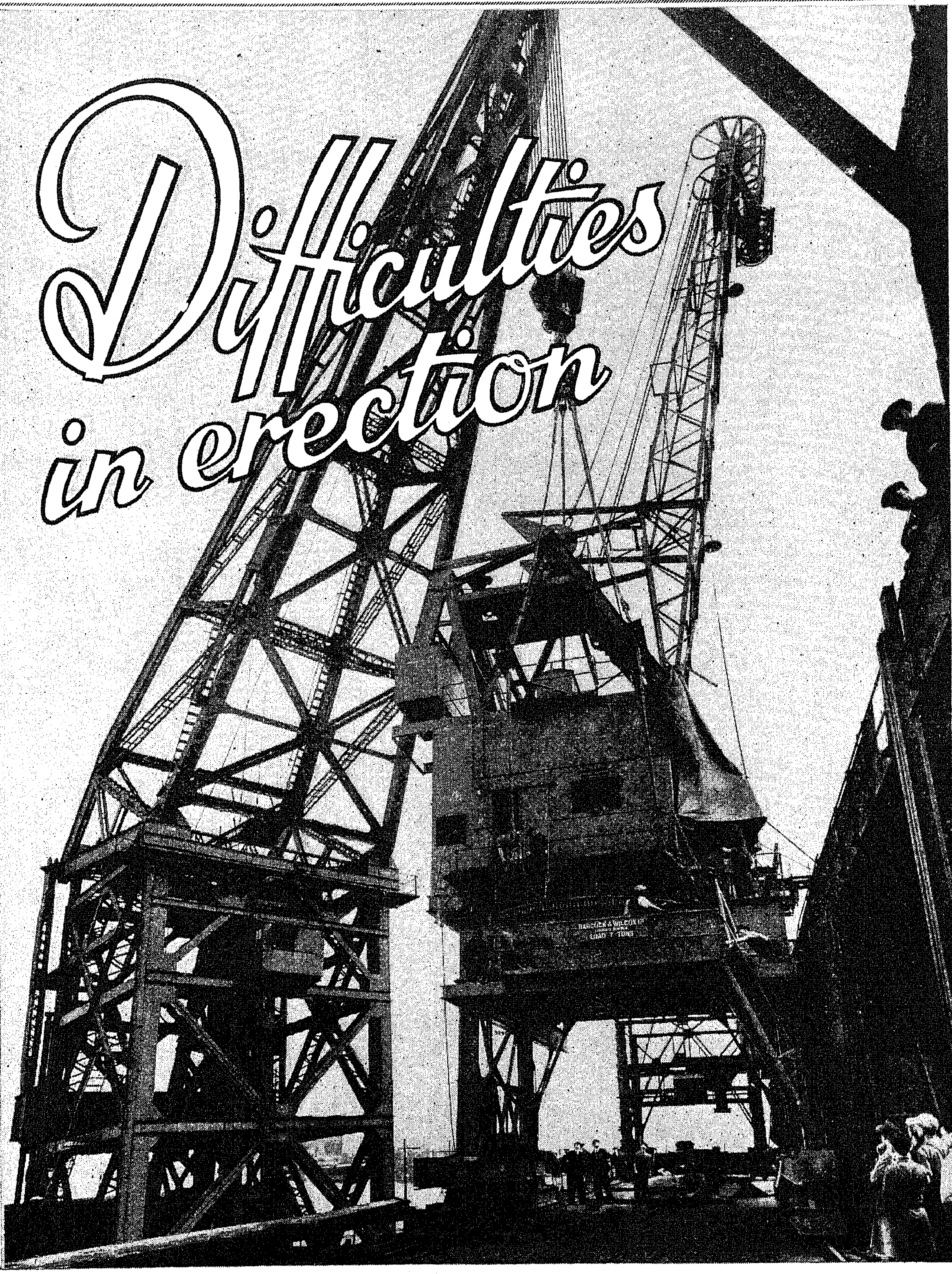
A meeting was also held on the 8th March, 1939, when a discussion took place on the subject of "Illumination"; 45 members and guests were present.

A further discussion was held on the 12th April, 1939, on the subject of "Radiocommunication," and a visit to Madras Broadcasting Station took place on the following day.

New Zealand

Local members of the I.E.E. were invited to attend a Conference at Wellington of the Electric Supply Engineers' Association on the 13th September, 1938, at which the paper by Mr. J. S. Pickles entitled "Rural Electrification" (see vol. 82, page 333), was read on behalf of the author by Mr. N. G. McLeod, Member. The attendance at the meeting was over 100 and an interesting discussion took place.

Thirty of the local members of the I.E.E. accepted an invitation to attend a meeting at Wellington of the New Zealand Institution of Engineers held on the 8th November, 1938, under the auspices of the New Zealand Standards Institute, at which Mr. P. Good, deputy director of the British Standards Institution, gave an Address on "The Scientific and Technical Aspects of Standardization."

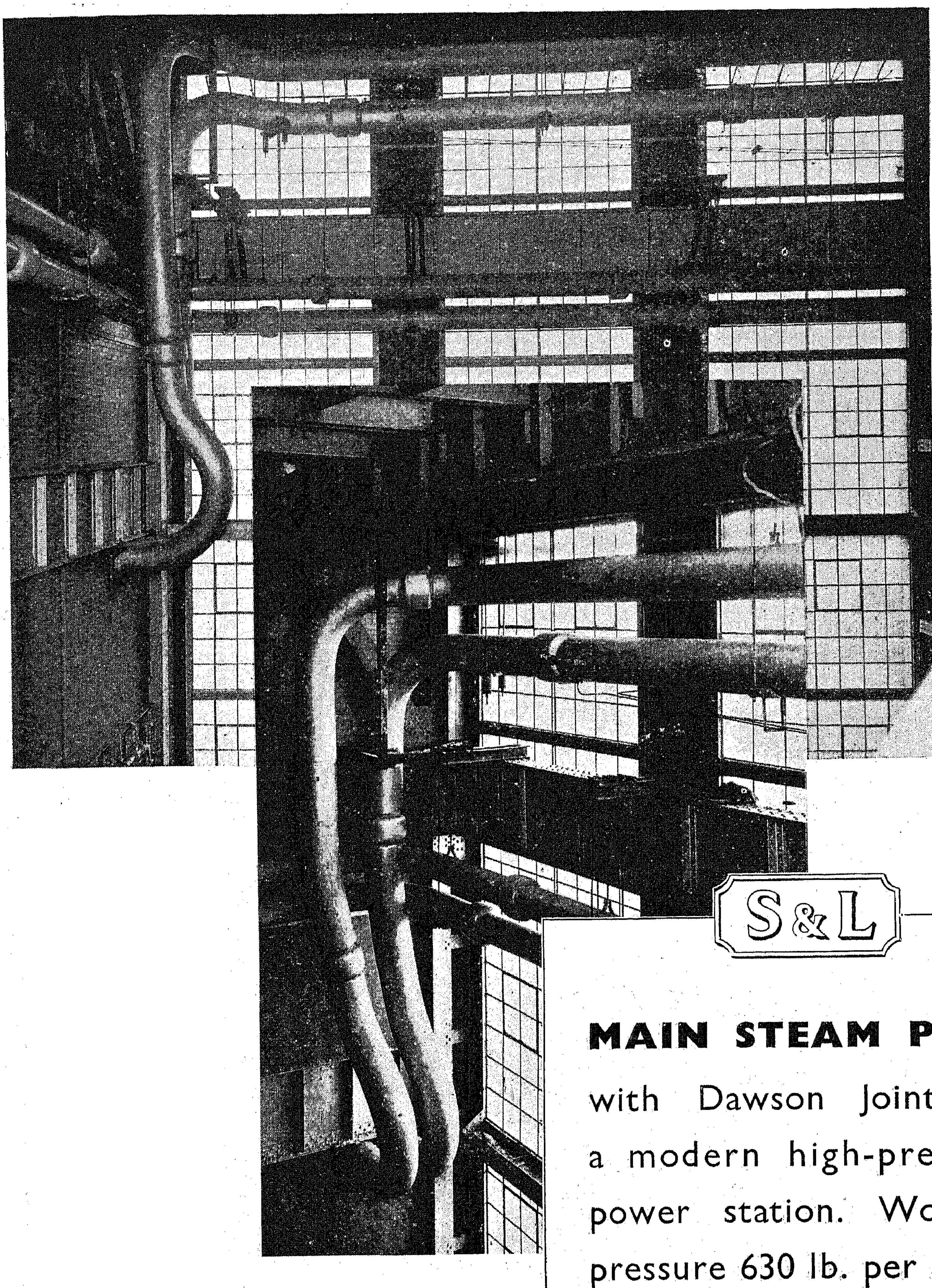


THE reasonable solution of difficulties peculiar to any phase of the steam raising problem is perhaps the chief reason for the position which we occupy in our particular industry. Apart from problems connected with design, difficulties have frequently to be surmounted when making shipment or in erection. Boilers have been transported by aeroplane, dog-sleigh, mule-pack, and coolie porterage, whilst on occasions boiler drums have been sealed up and floated across rivers.

It is not often that a crane is delivered completely erected, but in the instance shown in the photograph it was not convenient to do the erection at the site of the Greenwich Generating Station of the London Passenger Transport Board, so the difficulty was overcome by erecting the crane at Tilbury, from whence it was carried up the river to Greenwich by floating crane.

The crane is a Babcock & Wilcox Electrically Operated 7-ton Level Luffing Jib Crane.

BABCOCK & WILCOX LTD., 34 FARRINGDON STREET, LONDON, E.C.4



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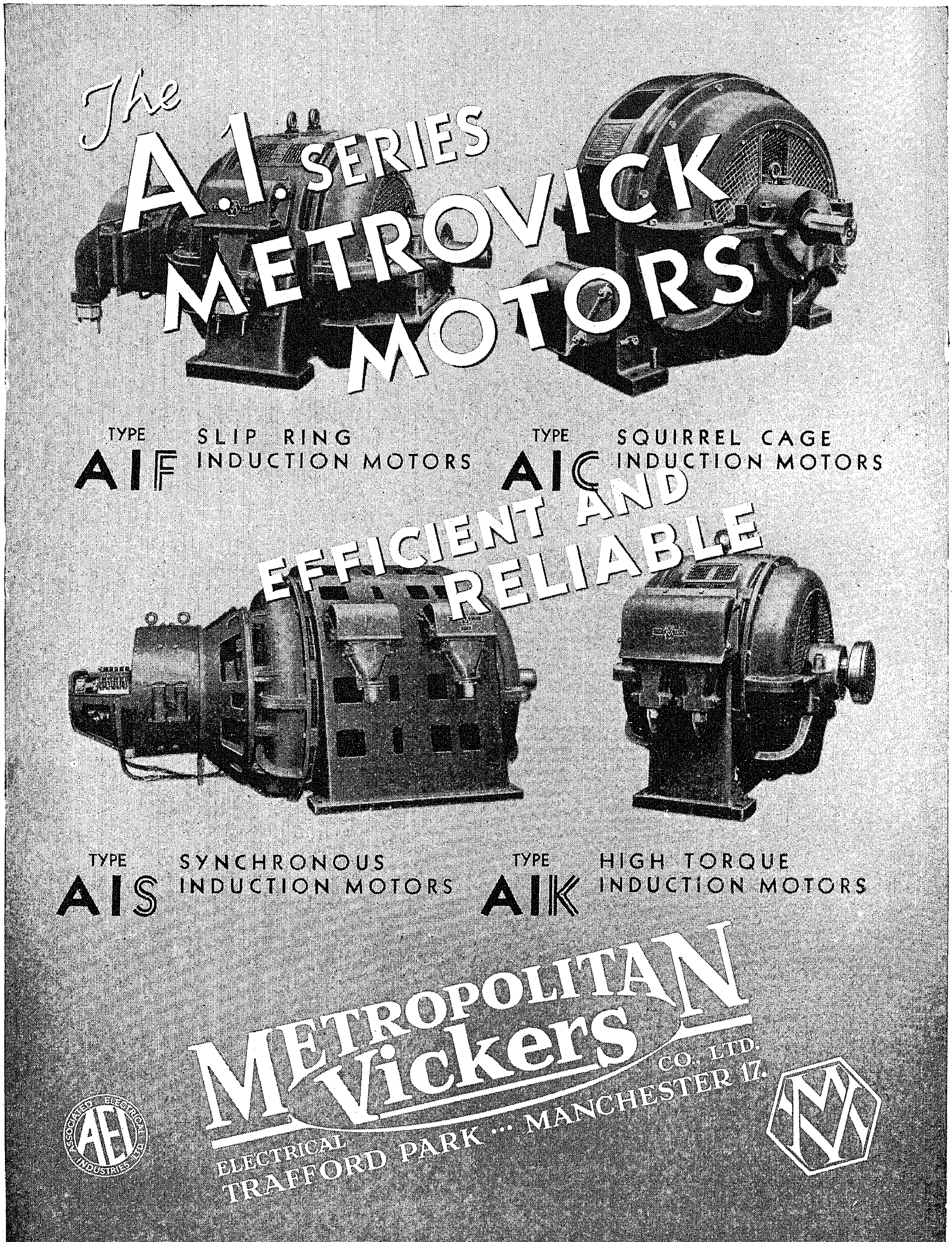
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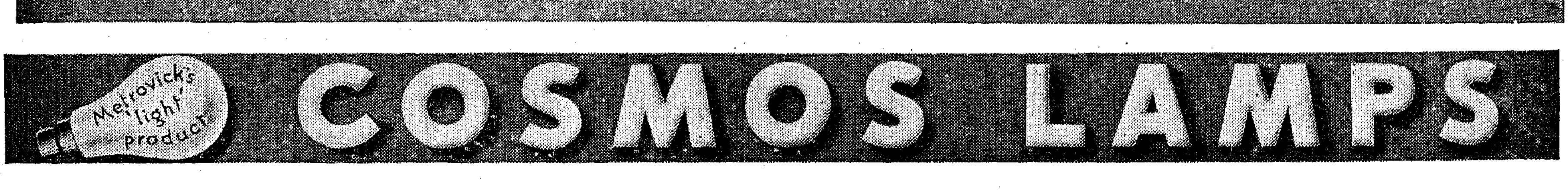
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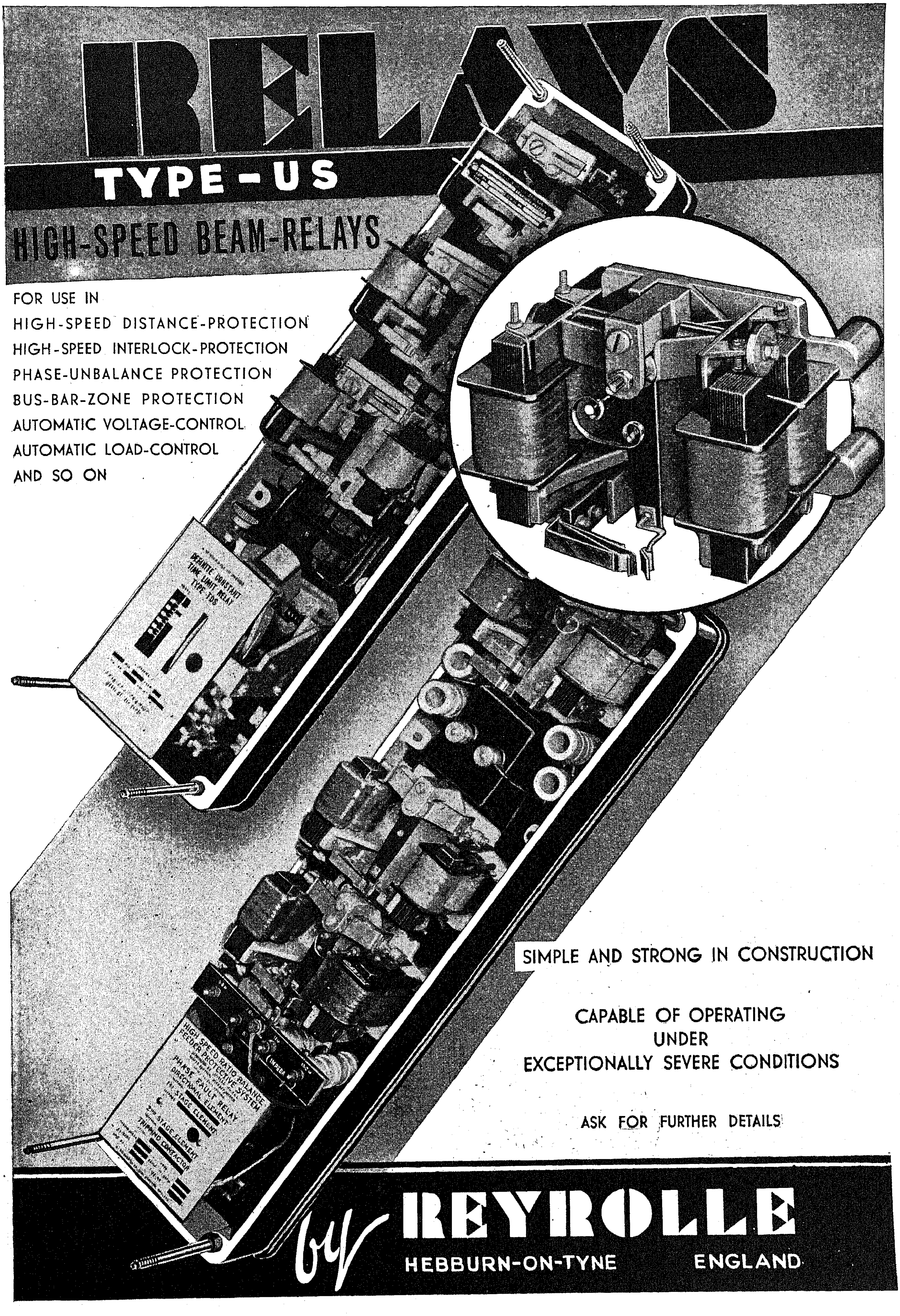
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